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FRAGMENT WEIGHT DISTRIBUTIONS FROM NATURALLY FRAGMENTING CYLINDERS LOADED WITH VARIOUS EXPLOSIVES

H. M. Sternberg

Naval Ordnance Laboratory
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By:
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EXPLOSION DYNAMICS DIVISION
EXPLOSIONS RESEARCH DEPARTMENT
NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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FRAGMENT WEIGHT DISTRIBUTIONS FROM NATURALLY FRAGMENTING CYLINDERS LOADED WITH VARIOUS EXPLOSIVES

This is the initial part of a one year effort to construct a scheme for the rapid calculation of fragment directions, velocities, and weight distributions from shells, bombs, and warheads. Previous work in this area has been collected, extended, and assembled into this report. Aside from its ultimate use in the fragment prediction scheme, the work is of interest in itself, since it compares fragmentation properties of a wide range of explosive compositions.

The work is being supported by the U.S. Army Materiel Systems Analysis Agency, under Task NOL-989/A, Fragment Prediction Method.

ROBERT WILLIAMSON II
Captain, USN
Commander

C. J. ARONSON
By direction

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I. Introduction

When a steel cylinder is filled with a high explosive and the explosive is detonated the fragment weight distribution depends on the location of the initiation point, or points, the cylinder diameter, the wall thickness, the type and treatment of the steel, and the composition and density of the explosive. A scheme to get the fragment weight distribution, analytically, once these variables are specified, has been a goal of warhead research for over thirty years. Two aspects of the problem are considered here, namely, the construction of a one parameter family of fragment weight distributions, and the assignment of values of this parameter to various high explosives, for one particular steel type, cylinder size, and initiation point location.

Two sets of fragment weight distribution data were used. The first set (the NWL data) is from work at the Naval Weapons Laboratory, Dahlgren, Virginia[1], on the effect of various steels and treatments on fragment size. It consists of data sheets covering 116 sawdust pit firings of Composition B loaded, uncapped, steel cylinders ranging in diameter from 40 mm to 8 in., with explosive/metal mass ratios (C/M) between 0.1 and 0.4. The second set of data (the NOL data) is mainly from a 1953 NOL report by Solem, Shapiro, and Singleton[2], where the effect of explosive composition on fragmentation was studied.

The examination of the NWL[1] and NOL[2] data showed that the commonly used Mott distribution[3] gives a reasonably good fit only in a central portion of the fragment weight range. There are more small fragments and fewer large fragments than the Mott formula predicts. This difficulty is overcome here with a more complete formula which involves only one independent parameter, conserves mass, and uses the Mott distribution where it applies. The measured weight distribution is somewhat dependent on the fragment recovery technique. In the NWL and NOL experiments considered here the ejected fragments were collected in sawdust, after crossing an air gap. This was followed by magnetic separation.

The analysis here makes use of the envelope of the fragment weight distribution curves. The envelope will be seen to have a central part

in the construction of the weight distribution formula, in finding the optimum value of the independent parameter for particular applications, and in comparing natural fragmentation with preformed or controlled fragments.

II. The Weight Distribution Formula

The following notation will be used. Let m be the fragment weight, in grains unless otherwise specified (7000 grains = 1 lb). For a particular metal casing, let $\tilde{W}_T$ be the total casing weight in grains, and let $\tilde{W}(m)$ and $\tilde{N}(m)$ be, respectively, the weight in grains and the cumulative number of fragments of weight greater than m. Let

$$\left.\begin{aligned} W &= \tilde{W}/\tilde{W}_T \\ N &= \tilde{N}/\tilde{W}_T \quad \text{(fragments/grain)}, \end{aligned}\right\} \qquad (1)$$

and

$$\bar{N} = 7000\ N \quad \text{(fragments/lb.)}$$

The symbols N and N(m) have the same meaning. Similarly, $\tilde{N} = \tilde{N}(m)$, $\tilde{W} = \tilde{W}(m)$, $W = W(m)$, $\bar{N} = \bar{N}(m)$.

Note that to conserve mass

$$dW = m\ dN\,. \qquad (2)$$

From this

$$\int_0^{\tilde{N}_o} m\ d\tilde{N} = \tilde{W}_T \quad ,$$

where $N_o = N(0)$, the total number of fragments. In normalized form

$$\int_0^{N_o} m\ dN = 1 \quad , \text{ or } \int_0^{\bar{N}_o} m\ d\bar{N} = 1 \qquad (3)$$

Here N_o is the total number of fragments per grain, and $\bar{N}_o$ is the total number of fragments per lb.

The Mott Formula for the fragment weight distribution can be written

$$N(m) = N_o \quad \exp\left[-(m/\mu)^{1/2}\right] , \qquad (4)$$

where N_o and μ are constants for a particular weight distribution. The value of the constant N_o in (4) is consistent with (3), i.e., $N_o = N(0)$, the total number of fragments per grain. The graph of (4) is a straight line in the $m^{1/2}$, log N plane, where $-\mu^{1/2}$ log e is the slope and log N_o is the ordinate intercept.

If the Mott formula is assumed to hold for the entire weight distribution then the constants N_o and μ are related, through the conservation of mass, by

$$N_o = 1/(2\mu). \tag{5}$$

To show this, note from (4) that $m = \mu[\ln(N_o/N)]^2$. Inserting this into (3) leads to (5). The Mott distribution is thus seen to depend on only one independent parameter.

The cylinder fragmentation data examined here shows that in most cases the Mott distribution (4) holds only over a central portion of the weight range. There are more small fragments and fewer large fragments than the Mott formula predicts. To account for this type of distribution a three part formula was constructed. Account is taken of the total weight of fragments weighing less than one grain, but the number and weight distribution of these fragments are not considered. The fragments weighing more than one grain are divided into three groups. The Mott formula (4) is used for the central portion of the fragment weight range, the Mott formula with the exponent 1/2 replaced by a value between 0.5 and 1 is used for the larger fragments, and a power law is used for the smaller fragments. The weight distribution is written

$$\text{I} : \quad N = N_1 m^p \quad , \quad m_1 < m \le m_2 \quad , \quad m_1 = 1 \tag{6}$$

$$\text{II} : \quad N = n_{II} \exp [-(m/\mu_{II})^{1/2}] \; , \quad m_2 < m \le m_3 \tag{7}$$

$$\text{III} : \quad N = n_{III} \exp [-(m/\mu_{III})^{q}] \; , \quad m > m_3 \tag{8}$$

The subscripts I, II, and III refer to regions and the subscripts 1, 2, and 3 refer to the region boundaries. As in the Mott formula, the distribution is assumed to be completely determined by a single parameter. The parameter used in the NWL work is used here, namely, $\overline{M}$, the average weight of fragments weighing more than one grain, i.e.,

$$\overline{M} = \widetilde{W}(1)/\widetilde{N}(1) = W(1)/N(1) \,. \tag{9}$$

The notation $N_j = N(m_j)$, $W_j = W(m_j)$ will be used. Thus, since $m_1 = 1$, the left boundary of Region I (Equation 6),

$$\widetilde{N}_1 = \widetilde{N}(1),\ \widetilde{W}_1 = \widetilde{W}(1),\ N_1 = N(1),\ W_1 = W(1),$$

but N_2 refers to the cumulative number of fragments, per grain, of weight greater than m_2 grains. In this notation $\overline{M} = W_1/N_1$.

Since the weight distribution is assumed to be entirely determined by the single parameter $\overline{M}$, the quantities N_1, n_{II}, n_{III}, μ_{II}, μ_{III}, p, q, m_2, and m_3, appearing in (6) - (8) are functions of $\overline{M}$.

The weight fraction of fragments weighing less than one grain was found from the experimental data in reference 1. The data were fitted to the form

$$\frac{\widetilde{W}_T - \widetilde{W}_1}{\widetilde{W}_T} = \frac{K}{\overline{M} + K} \,, \tag{10}$$

with K a constant. Then from (1), (9), and (10)

$$W_1 = \overline{M}/(\overline{M}+K) \,, \tag{11}$$

and

$$N_1 = 1/(\overline{M}+K) \,. \tag{12}$$

Here, W_1 and N_1 are, respectively, the weight fraction and number of fragments per grain, of weight larger than one grain. Note the distinction between W_1, the weight fraction weighing more than one grain and W_I, the weight fraction of fragments in Region I.

When the weight distributions N vs m are plotted for various values of the parameter $\overline{M}$, the curves are seen to have an envelope, determined by the condition

$$(\partial N/\partial \overline{M})_m = 0 \quad \text{(envelope)}. \tag{13}$$

From another viewpoint, this envelope is the locus of the maxima of the N vs $\overline{M}$ plotted for fixed values of m. Denote the envelope by $N_e(m_e)$ and note that m_e, and consequently N_e, is a function of $\overline{M}$.

An examination of available experimental[1,2] data shows that the envelope points (m_e, N_e) lie in Region II, or at the II-III boundary, for all values of $\overline{M}$ considered. We thus have, from (7) and (13), on the envelope

$$\frac{1}{n_{II}} \frac{dn_{II}}{d\overline{M}} - m_e^{1/2} \frac{d\mu_{II}^{-1/2}}{d\overline{M}} = 0 \quad \text{(envelope)}. \tag{15}$$

Now, (7) holds on the envelope, so that

$$n_{II} = N_e \exp [(m_e/\mu_{II})^{1/2}] . \tag{16}$$

Differentiating (16) with respect to $\overline{M}$ and combining the result with (15) leads to

$$\frac{d(m_e^{1/2})}{dN_e} = - \frac{\mu_{II}^{1/2}}{N_e} . \tag{17}$$

A satisfactory fit to the experimentally determined envelope had, for M larger than 4 grains, the form

$$m_e = C\overline{M}^{B_2} , \quad N_e = L/m_e \qquad (\overline{M} > 4 \text{ grains}) \tag{18}$$

where C, B_2, and L are constants. From (17) and (18),

$$\mu_{II} = (m_e/4) = (L/4N_e) = (C/4)\,\overline{M}^{B_2} , \tag{19}$$

and from (16), (18), and (19),

$$n_{II} = (L/C)\ \overline{M}^{-B_2}\ \exp[2] \quad . \tag{20}$$

Now, from (7) and (20),

$$N_2 = n_{II} \exp\left[-(m_2/\mu_{II})^{1/2}\right] , \tag{21}$$

and

$$N_3 = n_{II} \exp\left[-(m_3/\mu_{II})^{1/2}\right] . \tag{22}$$

Also, using (6) and (7) at the I-II boundary, the exponent p in (6) is

$$p = \ln (N_2/N_1)/\ln m_2. \tag{23}$$

To find n_{III}, q, and μ_{III} in (8), note first that, since (8) holds at the II-III boundary,

$$n_{III} = N_3 \exp\left[(m_3/\mu_{III})^{q}\right] , \tag{24}$$

where m_3 is known, from the experimental data. Now stipulate that N and $(\partial N/\partial m)_{\overline{M}}$ are continuous across the II-III boundary. This leads, using (7) and (8), to

$$\mu_{III} = \left[2qm_3^{\,q-1/2}\ \mu_{II}^{\,1/2}\right]^{1/q} \tag{25}$$

We can now get q, the exponent in III,by conserving mass, i.e., by satisfying (2). Denote the normalized weights of the fragments in each of the regions by W_I, W_{II}, and W_{III}. From (17),

$$W_I + W_{II} + W_{III} = \frac{\overline{M}}{\overline{M}+K} . \tag{26}$$

The weights W_I and W_{II} calculated with (2) are

$$W_1 = \frac{N_1}{1 + (1/p)}\left[1 - (N_2/N_1)^{(1 + 1/p)}\right] , \tag{27}$$

$$W_{II} = N_2 \, [m_2 + 2(m_2\mu_{II})^{1/2} + 2\mu_{II}] - N_3 \, [m_3 + 2(m_3\mu_{III})^{1/2} + 2\mu_{III}] \, . \tag{28}$$

Also, using (2),

$$W_{III} = \int_0^{N_3} \mu_{III} \, (\ln \frac{n_{III}}{N})^{1/q} \, dN \tag{29}$$

Equation (29) was solved for q by the method of false position, with the intergral evaluated by Simpson's rule at each stage. The quanity W_{III} is available from (26)-(28), while μ_{III}, and n_{III} are known functions of q from (24) and (25).

It turned out to be feasible to take the envelope of (7) as the II-III boundary, i.e., $m_3 = m_e$, $N_3 = N_e$.

To sum up, the fragment weight distribution (6)-(8) considered as a one parameter family, can be calculated once the weight fraction less than one grain, the envelope, and the region separation lines are obtained from the experimental data. The distributions need be calculated only once for each value of $\overline{M}$. To the extent that the one parameter assumption is valid, the entire weight distribution of fragments weighing more than one grain is determined, for a naturally fragmenting cylinder, by specifying the value of $\overline{M}$.

A computer program, in BASIC, to calculate the weight distribution with the scheme outlined in this section is listed in Table I. Table II is an outline of the computer program. It also contains a list of the parameters, the corresponding notations in the text, and the equations used to calculate them. Values of the parameters for the region divisions and the particular constants L, C, B_2, and K used here are listed, for various values of $\overline{M}$, in Tables III - VI. Tables III - V can be used to construct the weight distributions directly, from Equations (6)-(8), without the computer program. Table VI shows the weight fraction in each of the regions, for various values of $\overline{M}$.

III. The Fit to the Data

Both the NWL[1] and the NOL[2] data were used to make a fit to the form in Equations (6)-(8). Each data sheet furnished by NWL covered one sawdust pit firing and contained lists of the number and total weight of fragments in the weight ranges 0-1, 1-2, 2-5, 5-10, 10-25, 25-50, 50-75, 75-150, and over 150 grains. The NOL results[2] appear as plots of $N(m)$ vs m for 0.5 gram (7.7 grain) weight intervals starting at 0.5 grams. Each plotted point in the NOL report is an average of data from three different firings. The fit here was made entirely by plotting the data in convenient ways and drawing best lines by eye.

The weight fraction of fragments weighing less than one grain was found from the NWL data[1] alone (the smallest weight range in the NOL data is 0.5-1.0 gram). In Figure 1 the NWL data is used to plot, on reciprocal ruling paper, the percent by weight of fragments weighing less than one grain vs $\overline{M}$. Note, in the figure, that these fragments are 11% of the total weight when $\overline{M}$ is 5 grains, 6% when $\overline{M}$ is 10 grains and 2% when $\overline{M}$ is 30 grains. The data was fitted to (10), with $K = 0.6$, so that from (12),

$$\overline{N}_1 = 7000/(\overline{M}+0.6). \tag{30}$$

The envelope (18), constructed to fit both the NWL and the NOL data, is

$$m_e = 2050/\overline{N}_e = 0.236\ \overline{M}^{1.77} \quad (\overline{M} > 4 \text{ grains}). \tag{31}$$

A fit made for the boundary line between Regions I and II gave

$$m_2 = 1+(2/9)(\overline{M}-1)^{5/4}. \tag{32}$$

Recall, from Section II, that the envelope will be taken as the boundary between Regions II and III, i.e.,

$$m_3 = m_e . \tag{33}$$

The remaining quantities in the weight distribution formula (6)-(8) can now be calculated by the method outlined in Section II. We get μ_{II}, n_{II}, N_2, N_3 and p from (19)-(23), and q, n_{III} and μ_{III} by the numerical solution of (24), (25) and (29).

The region boundaries (32) and (33) are shown in Figure 2. The exponent q, used in Region III, is plotted vs $\overline{M}$ in Figure 3. Figure 4 shows the weight distributions for several values of $\overline{M}$ calculated from (6)-(8) and (30)-(33). The heavy straight lines correspond to Region II where the Mott distribution with the exponent 0.5 is used. In Figure 5 the fit to the weight distributions is plotted in a different way, as $\overline{N}(m)$ vs the parameter $\overline{M}$ for fixed values of m. The curve for m = 1 is just (30).

The NWL data were plotted in the form shown in Figure 5 by taking, for each m corresponding to the end of a weight interval, one $\overline{M}$ point from each data sheet. In Figure 6 the data is shown in this form together with the fitted curves in Figure 5. The maxima of some of the fitted curves is a bit higher than a best fit to the data would give. This came about from the imposed requirement that a single fit be made to both the NWL and the NOL data.

IV. Effect of Explosive Composition

The NOL results consist of the data for 15 different explosives treated in NAVORD Report 2933[2], together with unpublished data for eight additional explosives. These additional data, obtained in 1952-1953, were taken from NOL Project Notebook 4352. In all cases the explosives were loaded into AISI 1045 steel tubes, 9 inches long, 2.0 inches ID, 2.5 inches OD, with a hardness about Rockwell 100-B. The experimental arrangement is shown in Figure 7. Since the densities of the various explosives are different, the explosives are being compared on a volume, rather than weight, basis. The cylinder breakup will vary with the method of initiation, the wall thickness, the cylinder diameter, and the type of steel, as well as with the explosive composition. Hence, the values of $\bar{M}$ obtained for the different explosives apply only to this system.

To assign a value of $\bar{M}$ to each explosive, the weight distributions were first calculated with (6)-(8) for values of $\bar{M}$ ranging from 4 to 50 grains at intervals of 0.5 grains. Then, for each explosive, the weight distributions corresponding to the different values of $\bar{M}$ were superimposed on the data points and the value of $\bar{M}$ which fit the data best was selected.

The NOL data for the various explosives, together with the calculated weight distribution corresponding to the assigned $\bar{M}$ values, are shown in Figure 8.

Results for all the explosive compositions studied are summarized in Tables VII and VIII. Note here that the smallest value of $\bar{M}$, 10.5, was obtained with (90/10) BTNEN/Wax. Among the explosives practical for military use Composition B and Composition A3, both with $\bar{M}$ = 12, are at the low end of the range. The fragmentation from these is significantly finer than that from cast TNT($\bar{M}$ = 17.5) or pressed TNT($\bar{M}$ = 22). Fragmentation from some of the aluminized compositions is in between that from Composition B and TNT. For example, $\bar{M}$ is 13.5 for HBX-1, 15.5 for H-6, and 17 for Tritonal. Note that 80/20 Ammonium Nitrate/TNT produced the largest average fragment weight, with $\bar{M}$ = 45.

V. Comparison with Preformed Fragments

The concept of a design weight m_d is useful in connection with applications. One wishes to maximize $N(m_d)$, the number of fragments weighing more than m_d grains. For each design weight m_d there will be a value of $\overline{M}$, corresponding to a weight distribution, for which $\overline{N}(m_d)$ is a maximum (set $m = m_d$ in Figure 6). The locus of these maxima for different values of m_d is the envelope (13), also shown in Figure 6.

The relation between preformed and natural fragmentation for a given design weight is shown in Figure 9. This contains a log $\overline{N}$ vs log m plot of the weight distributions from natural fragmentation for different values of $\overline{M}$, calculated with (6)-(8). The envelope, for $\overline{M}$ bigger than 4 grains, is a straight line parallel to $7000/m_d$, the number of fragments available from preformed fragmentation. A comparison of the envelope and the preformed fragment line shows that the upper bound for $\overline{N}(m_d)$ from natural fragmentation is 29% (100×2050/7000 - see Sections II and III) of $\overline{N}(m_d)$ from uniform fragments of weight m_d. This upper bound for natural fragmentation is solely a property of the way the steel casings break up. In any particular instance, it may not be attainable, because of cost, strength, or material availability problems.

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2. A. D. Solem, M. Shapiro, and B. N. Singleton, Jr., "Explosives Comparison for Fragmentation Effectiveness," U.S. Naval Ordnance Laboratory, White Oak, Maryland, NAVORD Report 2933, 11 Aug 1953.

3. See R. W. Gurney and J. N. Sarmousakis, "The Mass Distribution of Fragments from Bombs, Shells, and Grenades," Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, BRL Report No. 448, 7 Feb 1944.

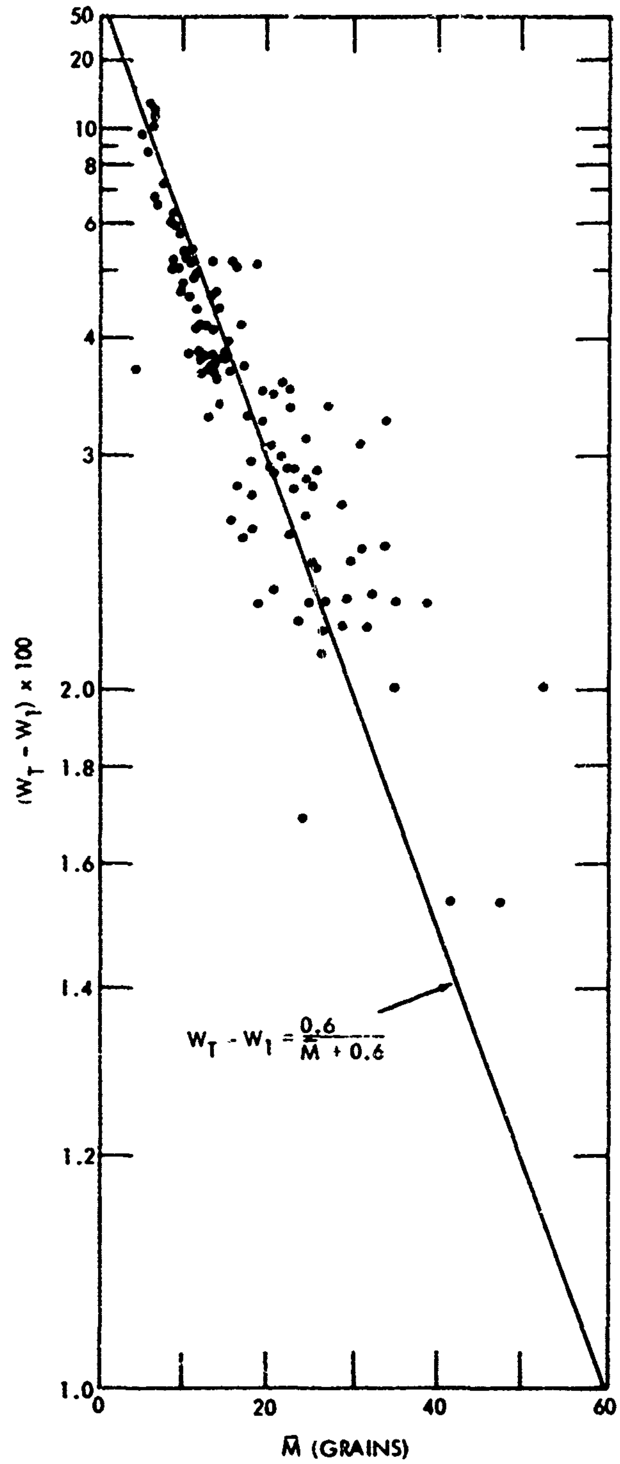

FIG. 1 PERCENT BY WEIGHT OF FRAGMENTS WEIGHING LESS THAN ONE GRAIN.

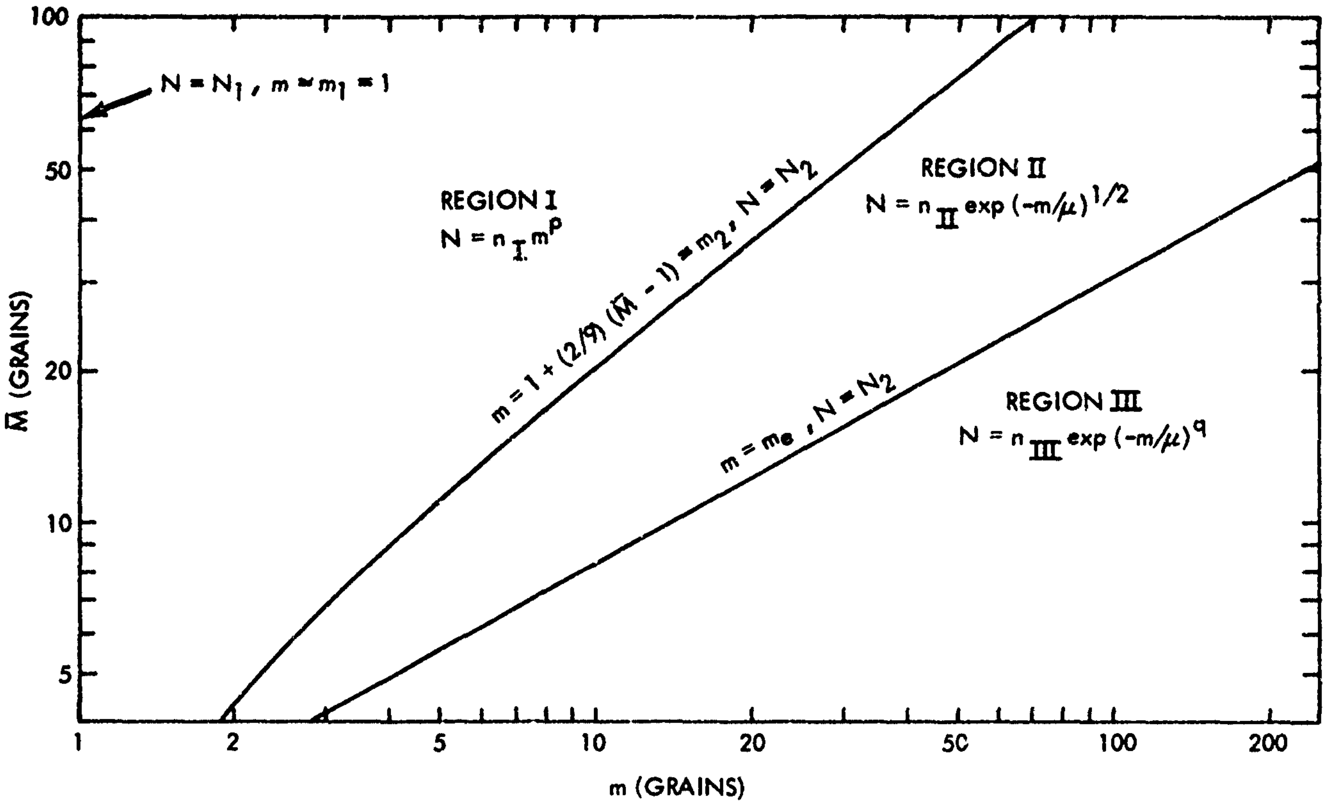

FIG. 2 REGIONS USED FOR THE FRAGMENT WEIGHT DISTRIBUTION FORMULA

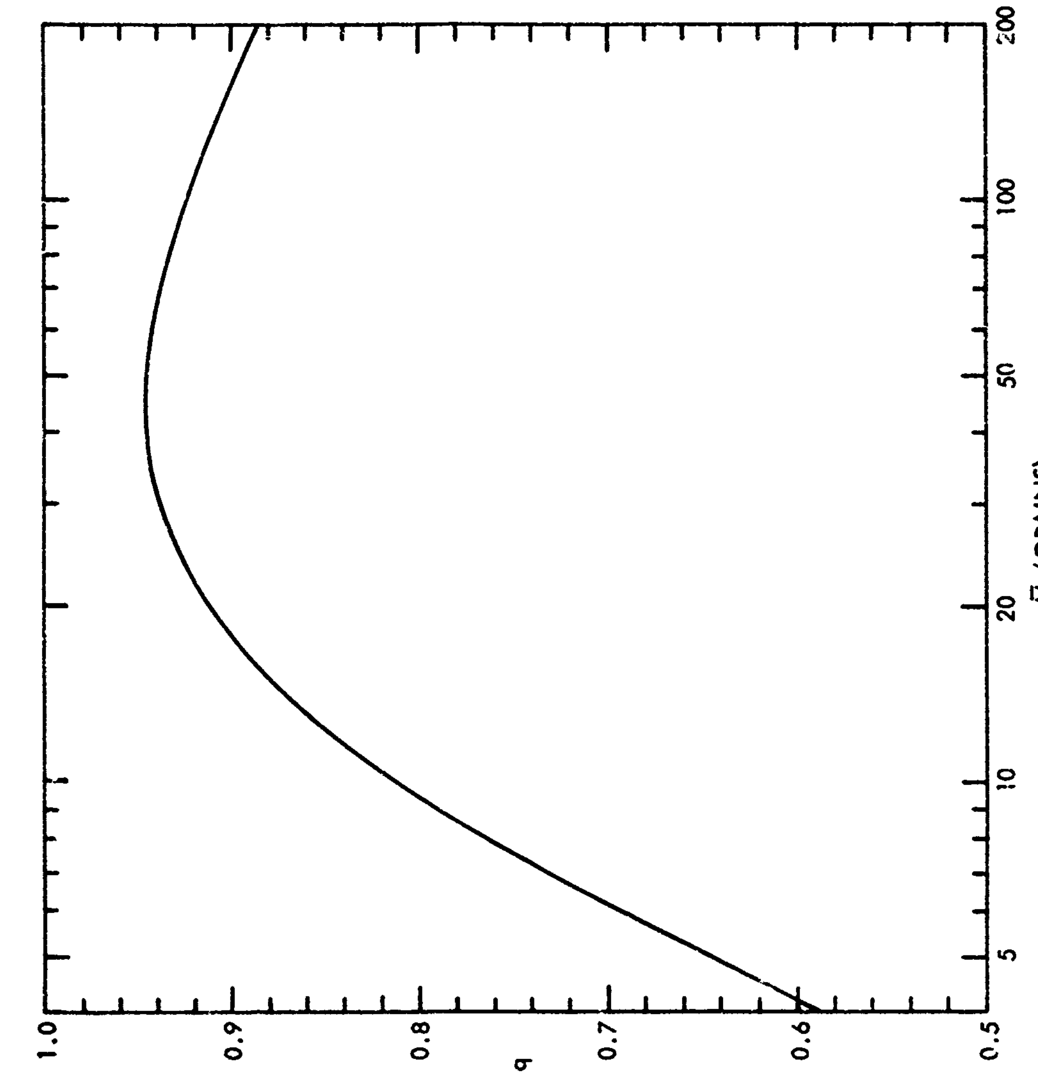

FIG. 3 THE EXPONENT q, USED IN REGION III, VS $\bar{M}$

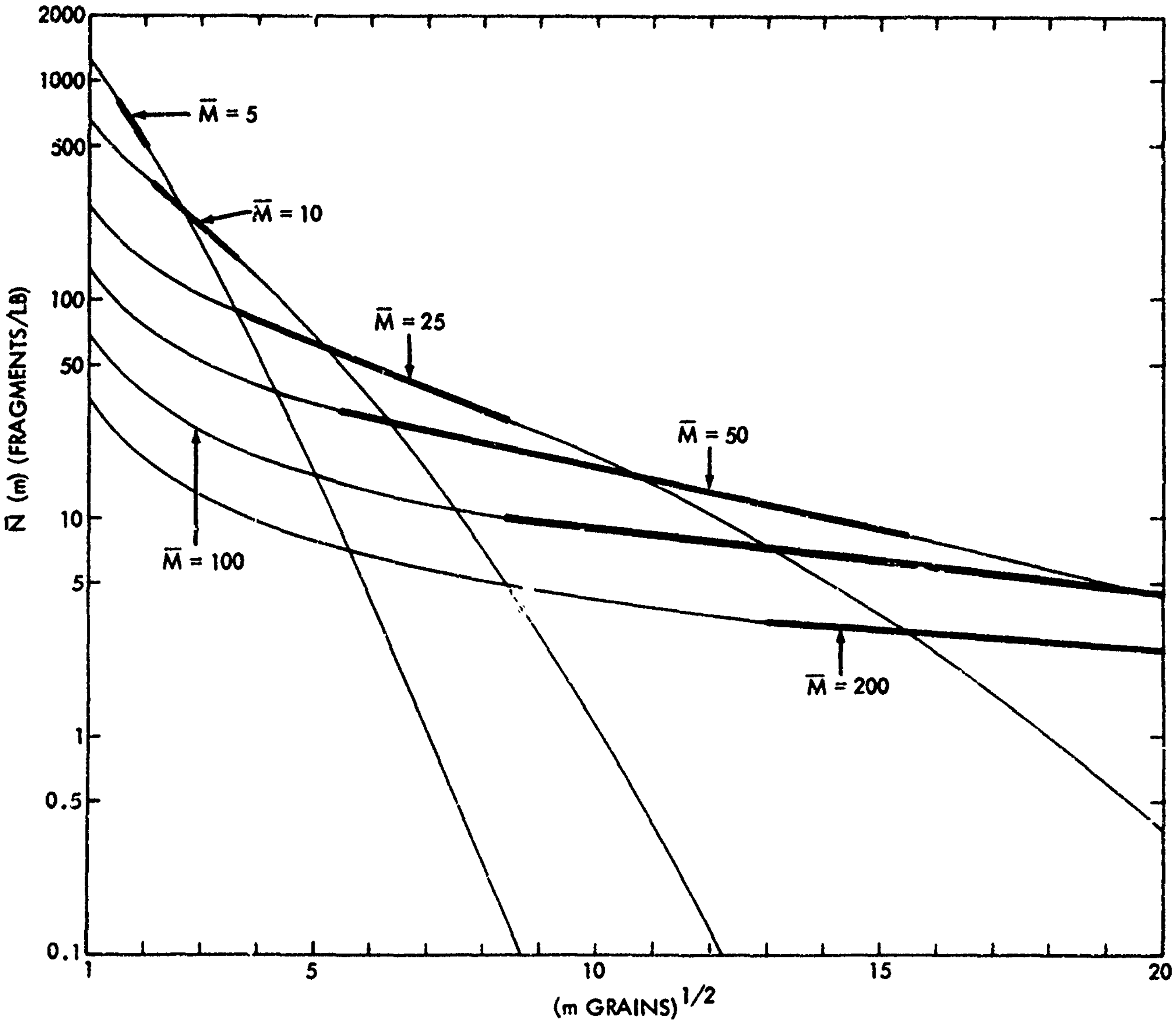

FIG. 4 FRAGMENT WEIGHT DISTRIBUTIONS FOR SEVERAL VALUES OF $\bar{M}$. CALCULATED WITH EQUATIONS (6) - (8).

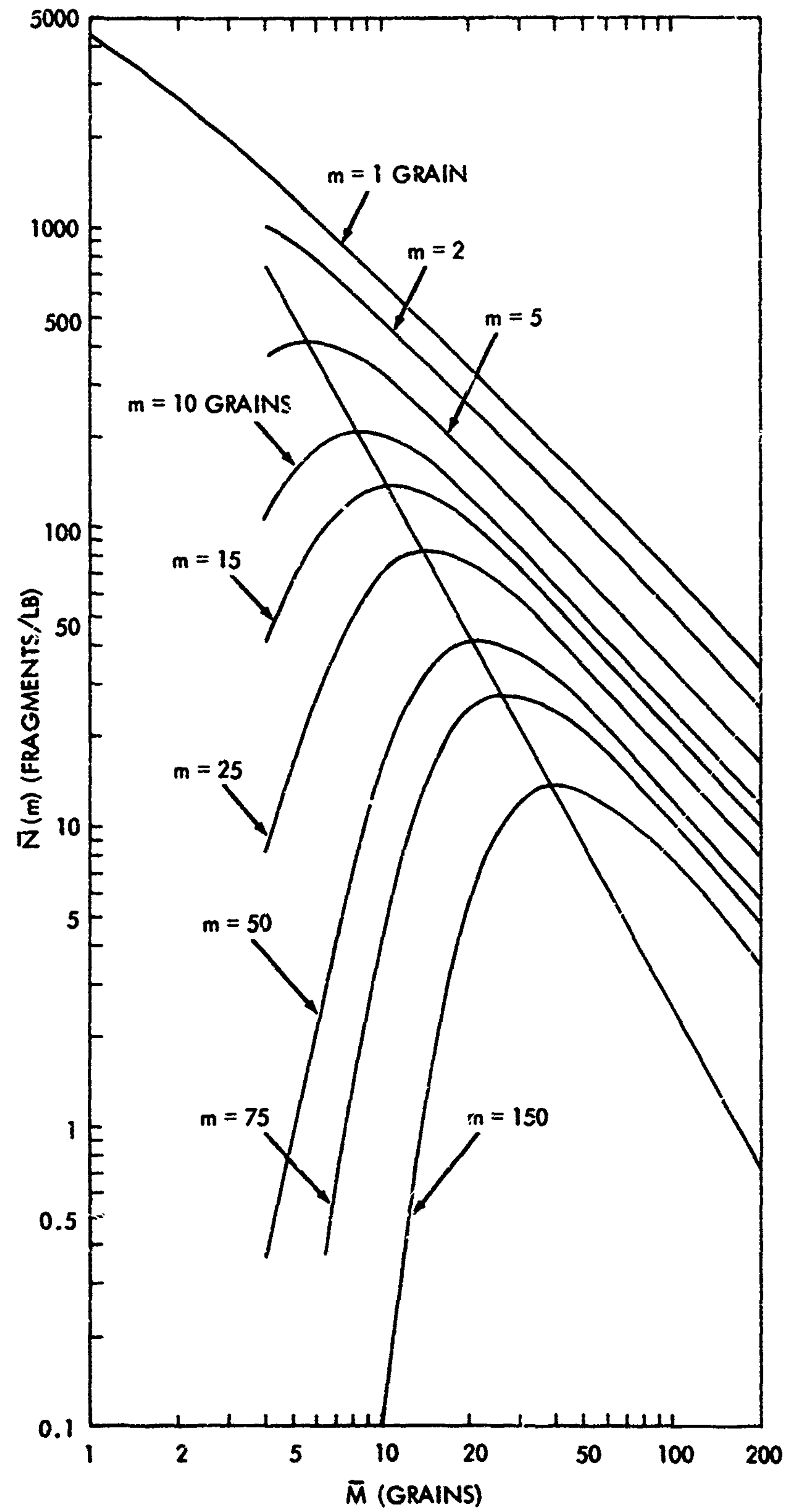

FIG. 5 $\bar{N}(m)$ VS THE PARAMETER $\bar{M}$ FOR FIXED VALUES OF m. CALCULATED WITH EQUATIONS (6) - (8).

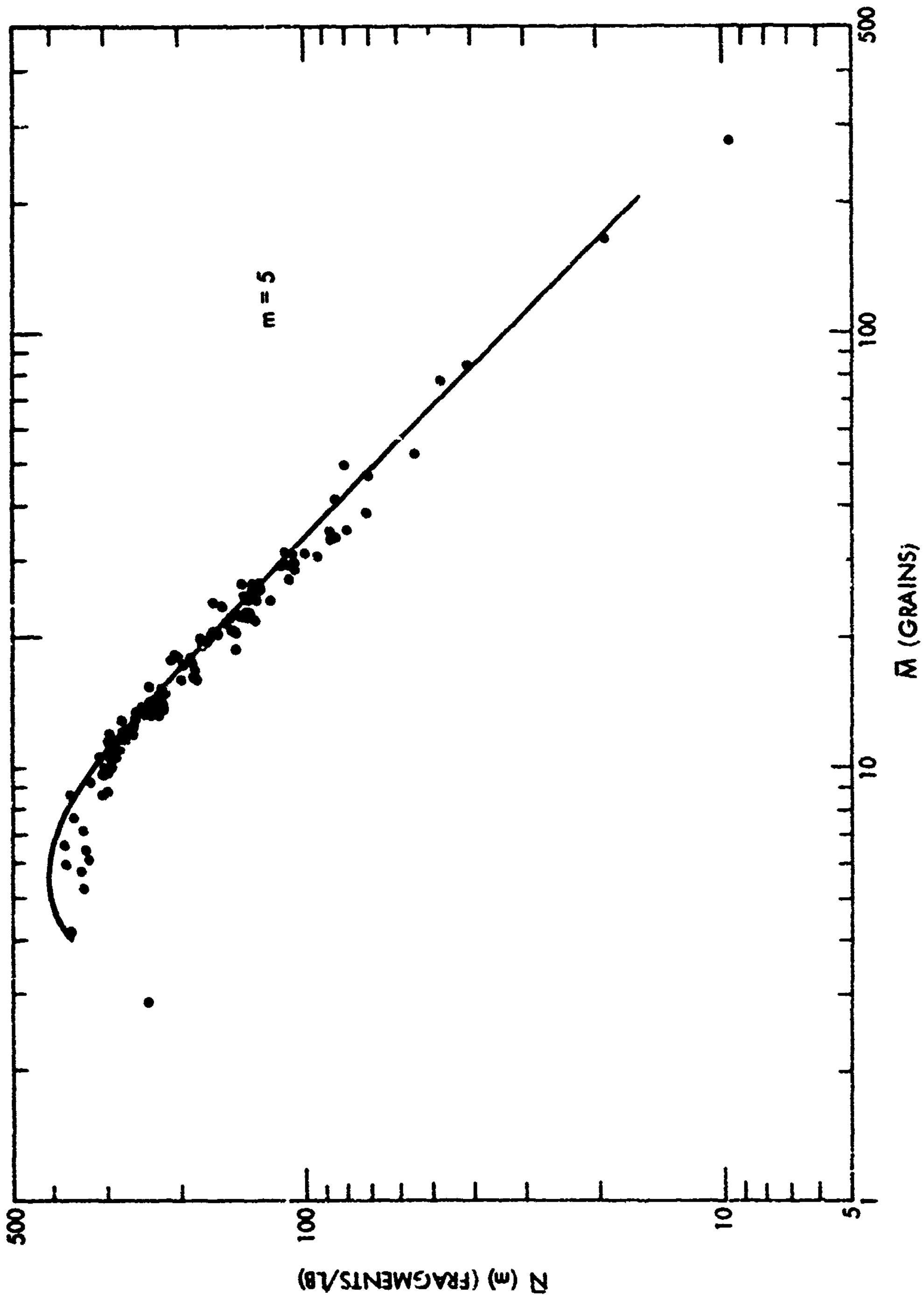

FIG. 6-1 THE NWL DATA (SUPPLEMENT TO REF 1). THE FITTED CURVES WERE CALCULATED WITH EQUATIONS (6) - (8).

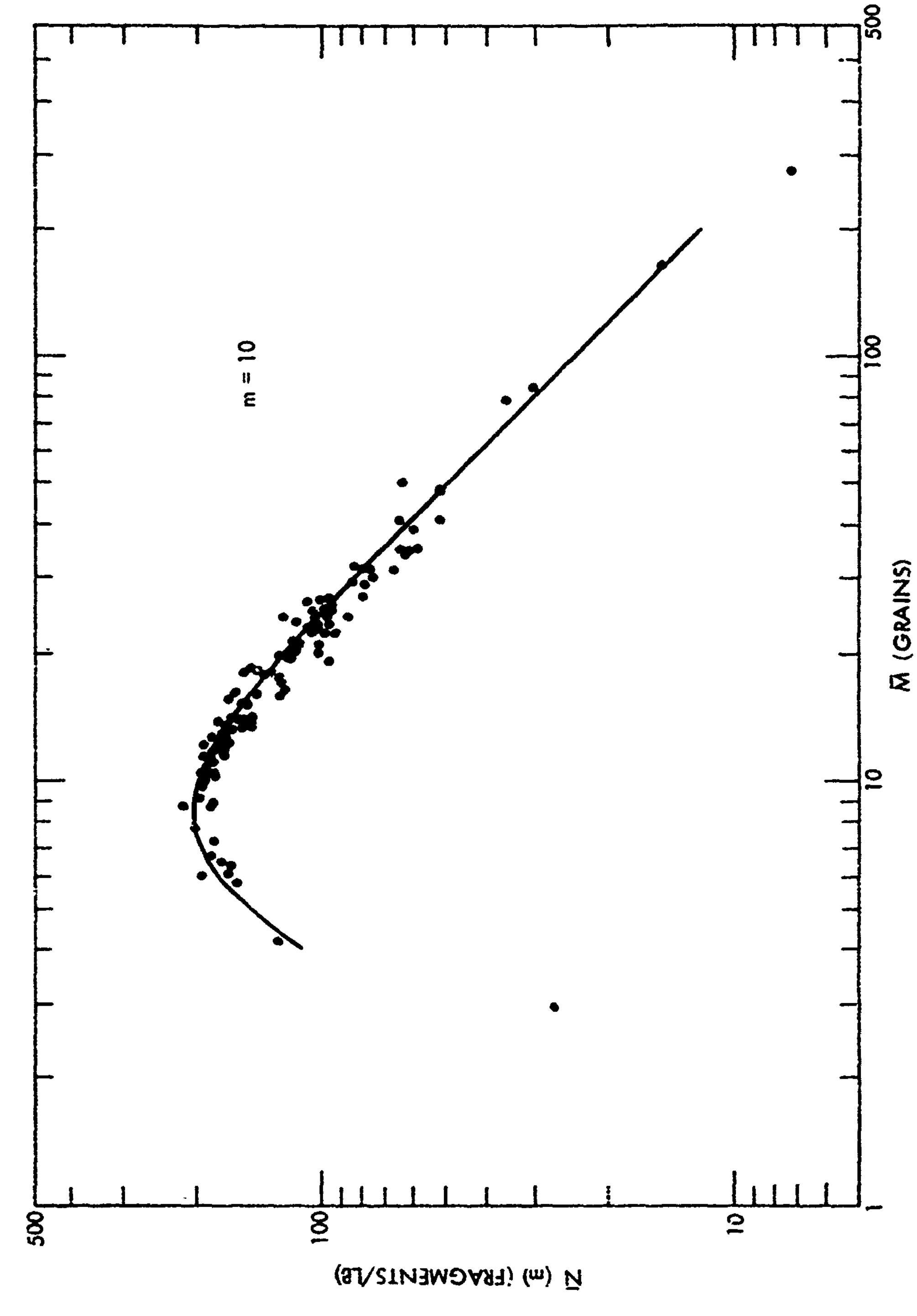

FIG. 6-2 THE NWL DATA (SUPPLEMENT TO REF 1). THE FITTED CURVES WERE CALCULATED WITH EQUATIONS (6) - (8). (CONT)

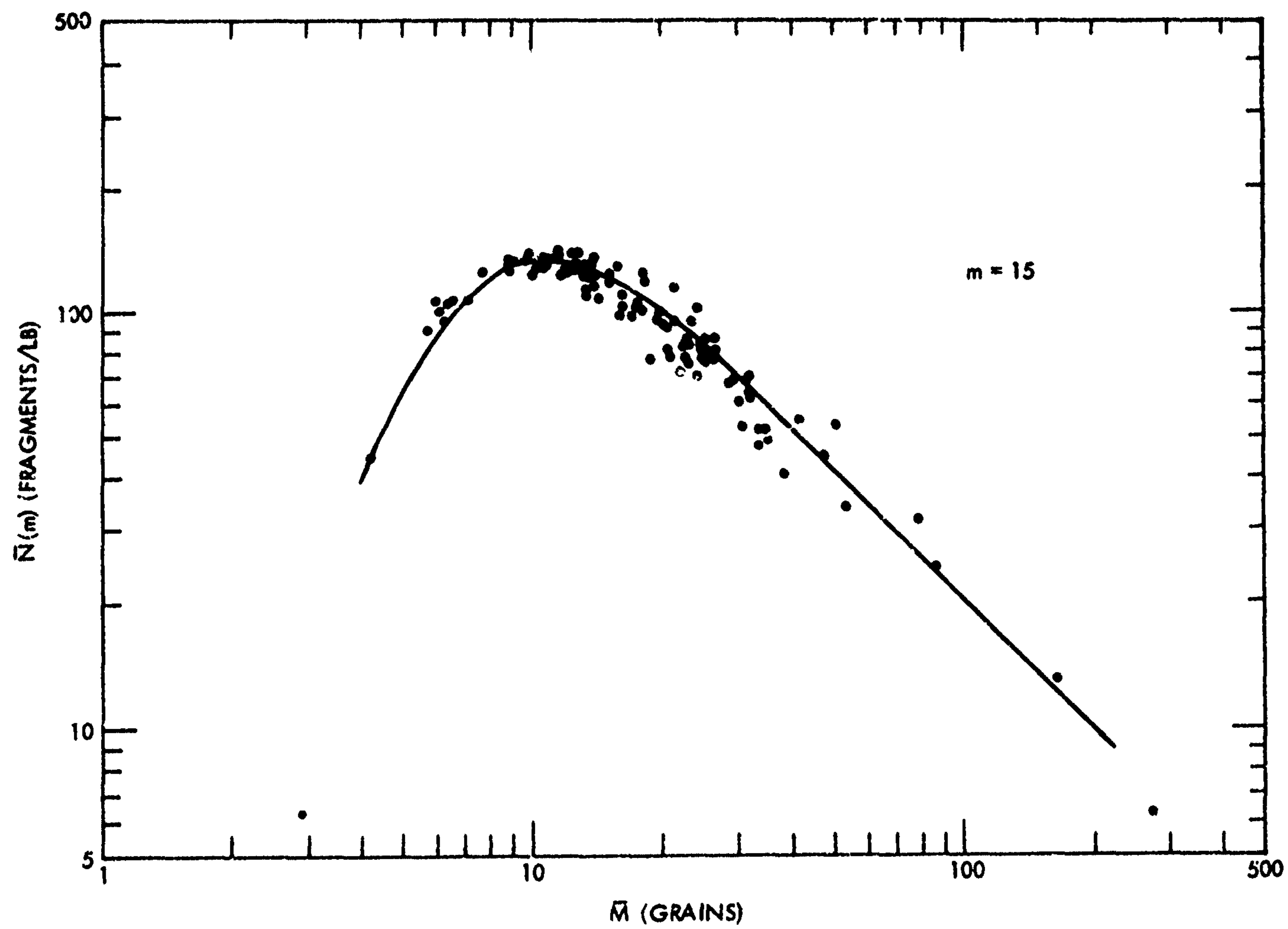

FIG. 6-3 THE NWL DATA (SUPPLEMENT TO REF 1). THE FITTED CURVES WERE CALCULATED WITH EQUATIONS (6) - (8). (CONT)

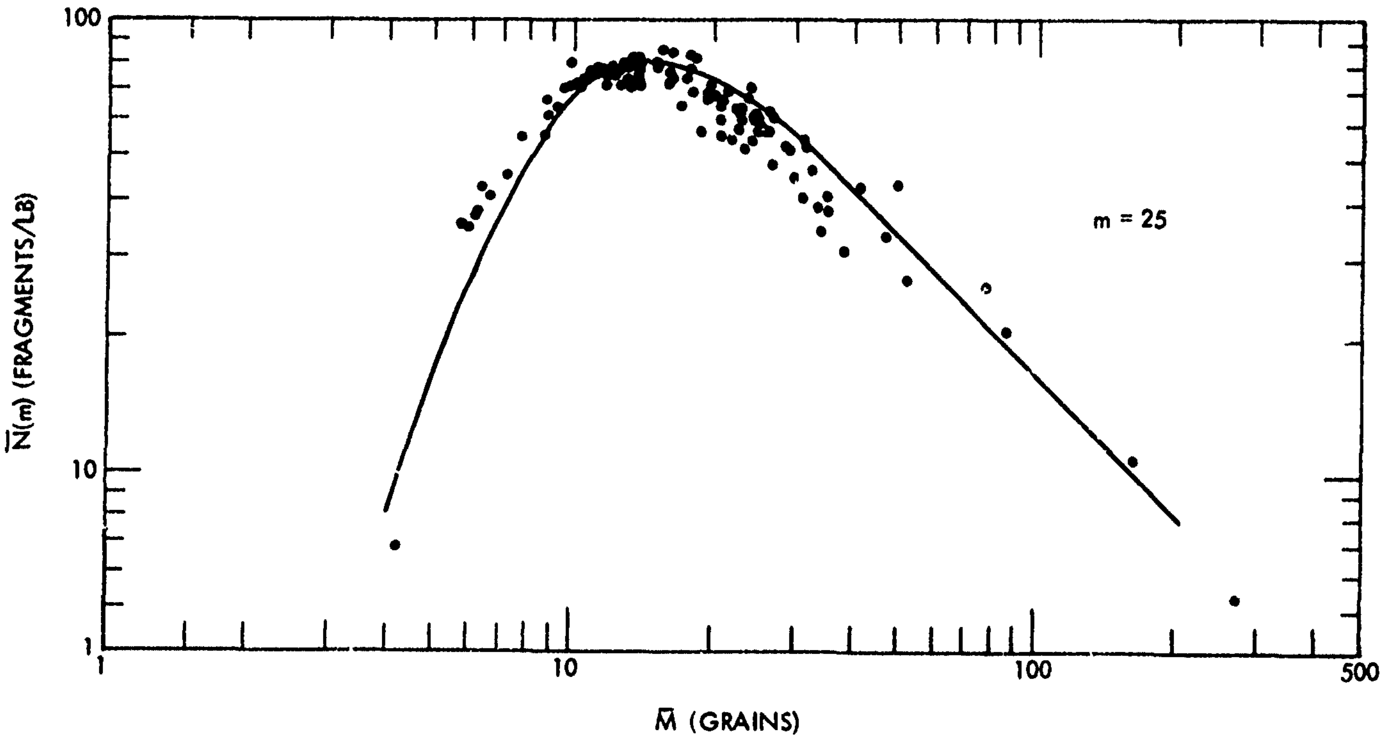

FIG. 6-4 THE NWL DATA (SUPPLEMENT TO REF 1). THE FITTED CURVES WERE CALCULATED WITH EQUATIONS (6) - (8). (CONT)

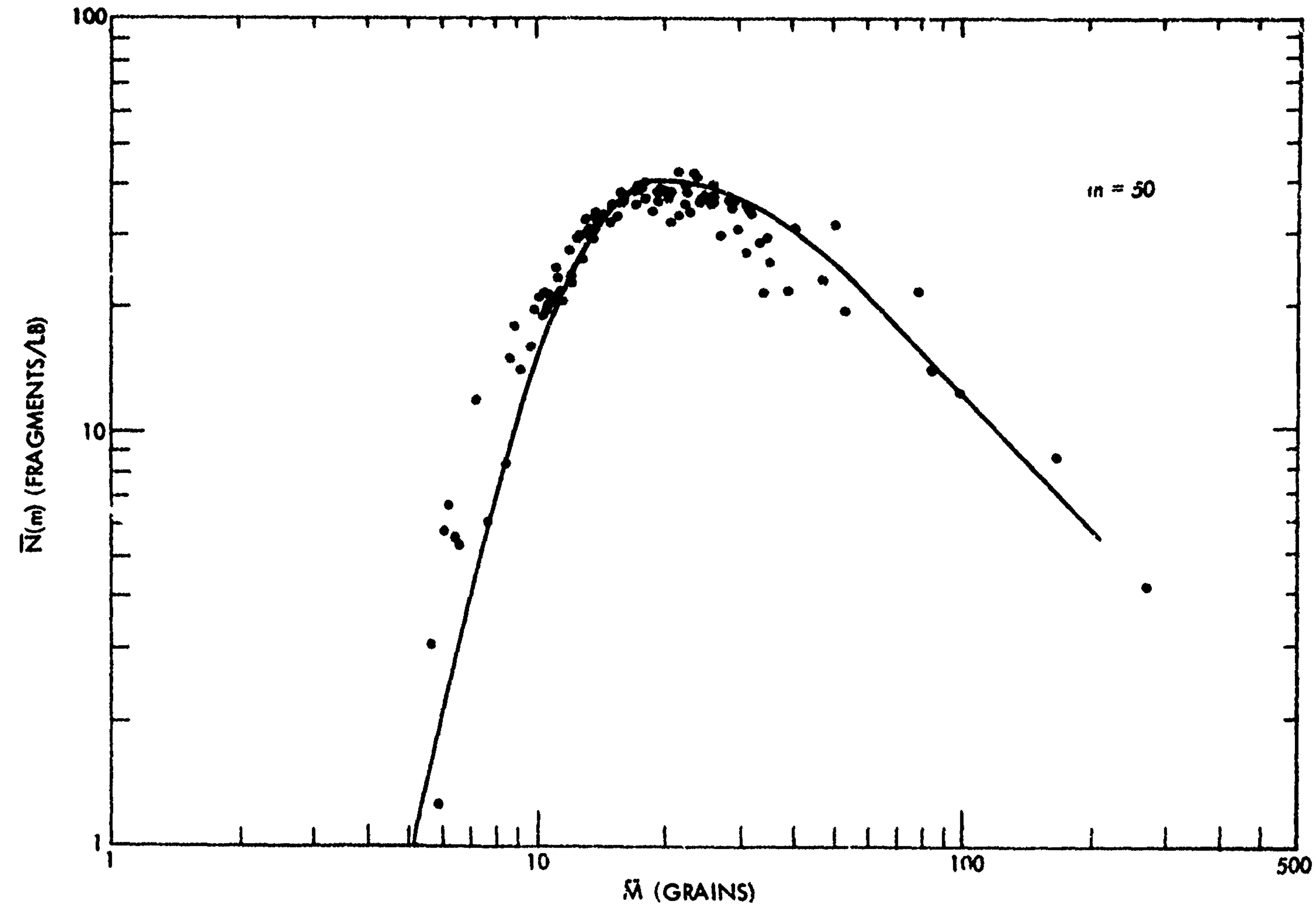

FIG. 6-5 THE NWL DATA (SUPPLEMENT TO REF 1). THE FITTED CURVES WERE CALCULATED WITH EQUATIONS (6) - (8). (CONT)

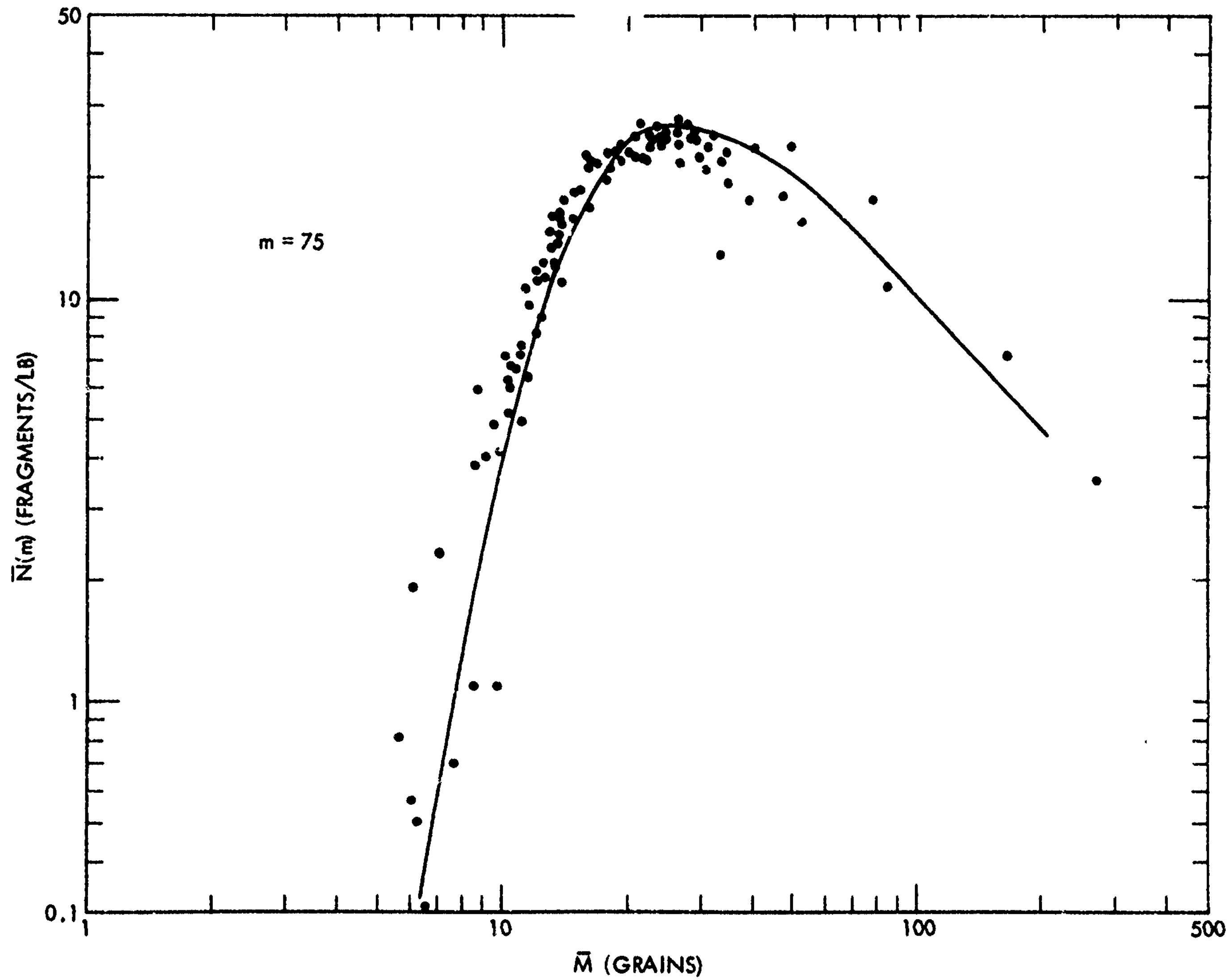

FIG. 6-6 THE NWL DATA (SUPPLEMENT TO REF 1). THE FITTED CURVES WERE CALCULATED WITH EQUATIONS (6) - (8). (CONT)

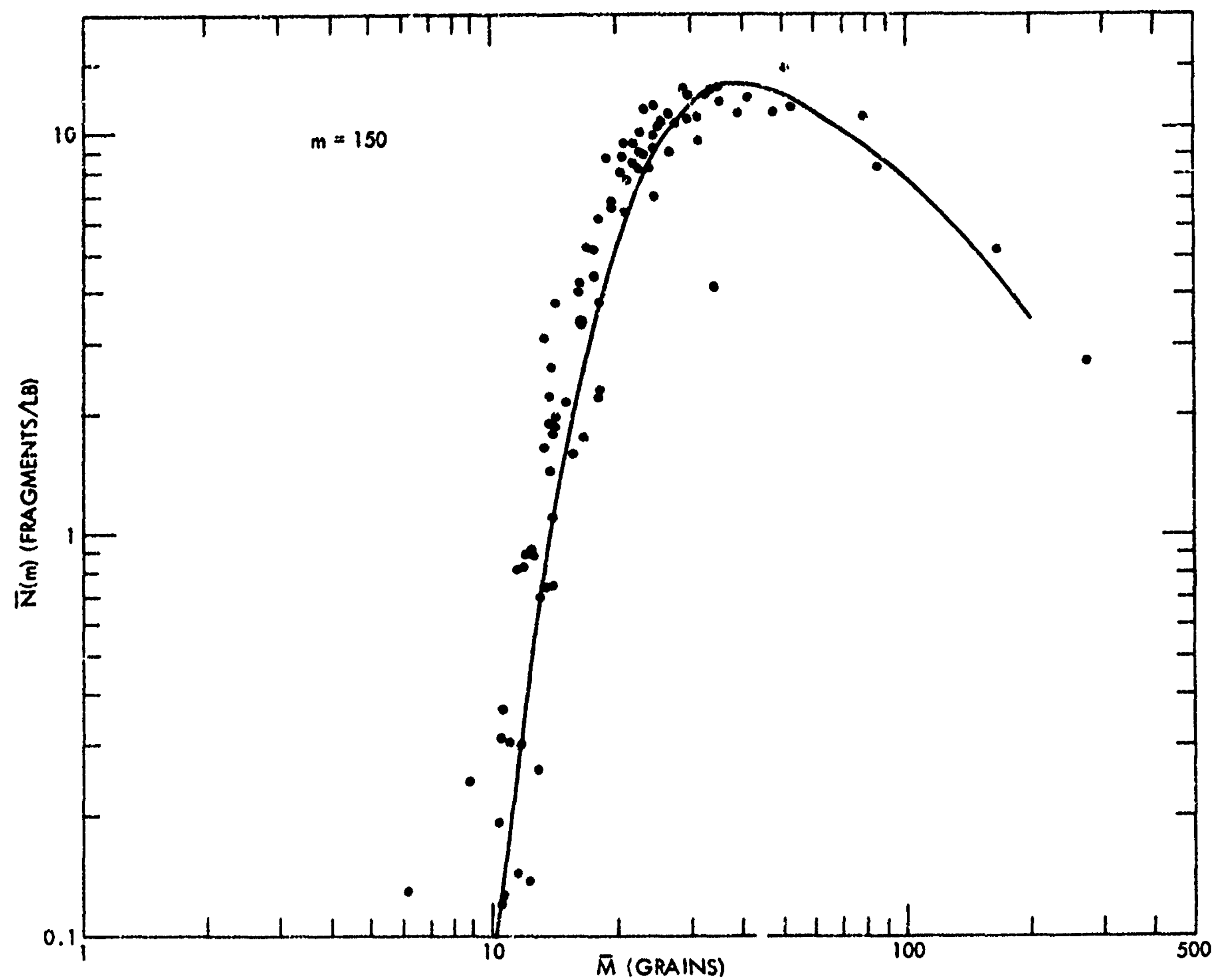

FIG. 6-7 THE NWL DATA (SUPPLEMENT TO REF 1). THE FITTED CURVES WERE CALCULATED WITH EQUATIONS (6) - (8). (CONT)

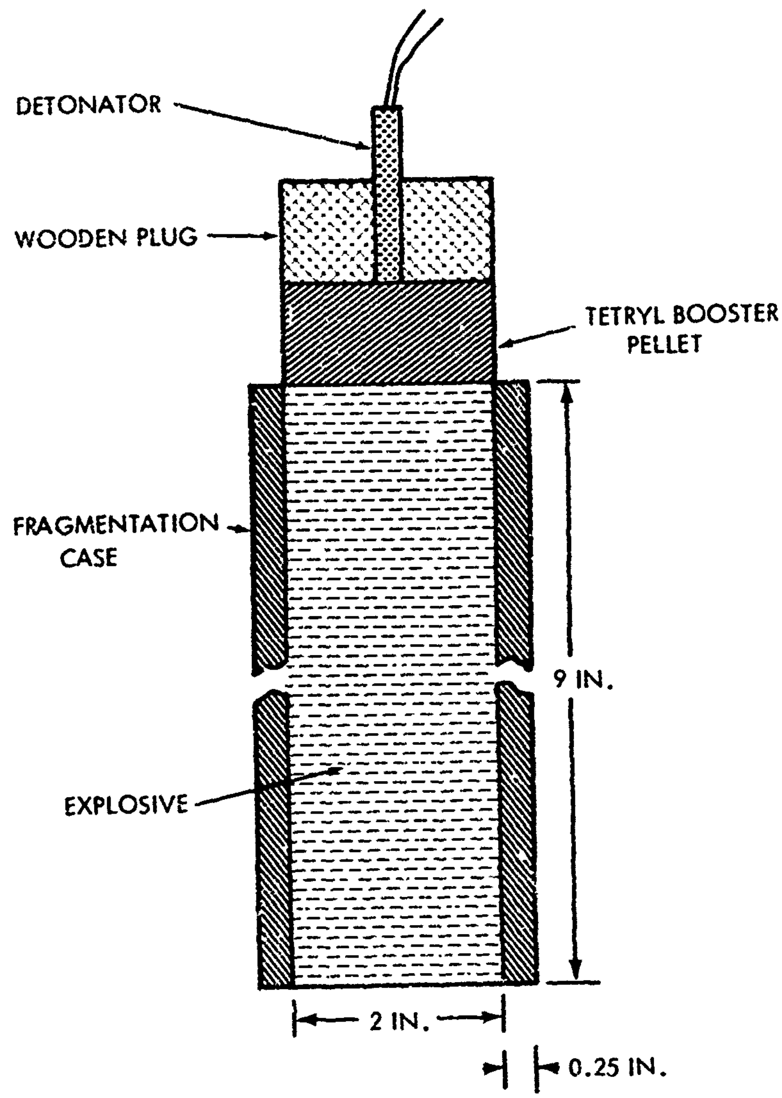

FIG. 7 ARRANGEMENT OF CHARGE AND INITIATOR FOR FIRING OF NOL CHARGES (NAVORD REPORT 2933)

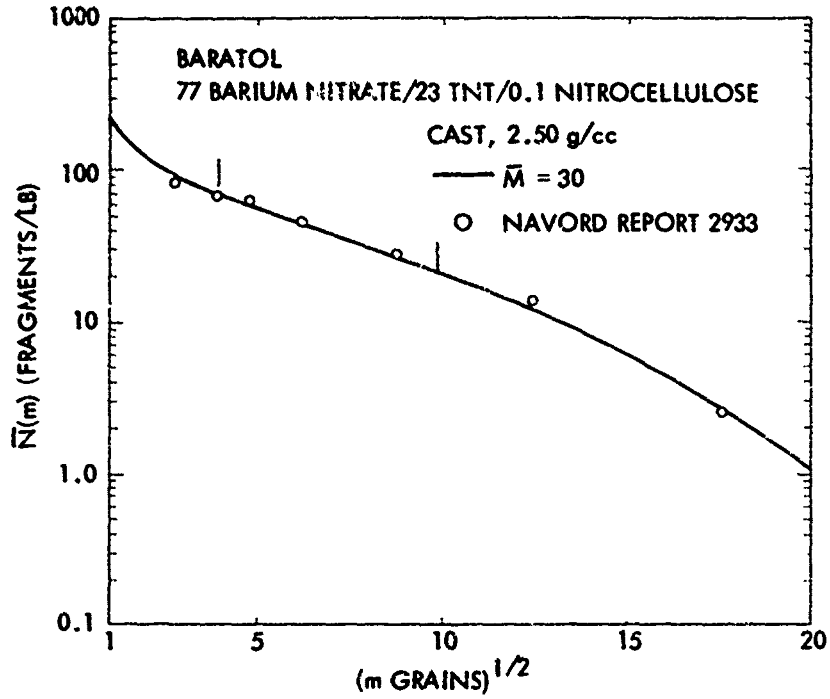

FIG. 8-1

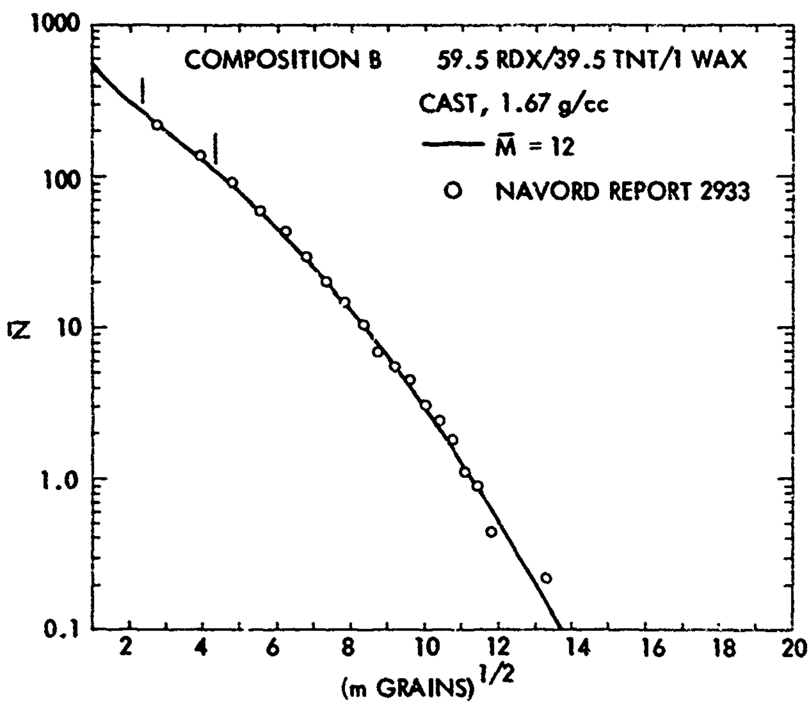

FIG. 8-2

FIG. 8 CUMULATIVE FRAGMENT WEIGHT DISTRIBUTION (2 IN. ID - 2.5 IN. OD CYLINDER FRAGMENTATION TEST)

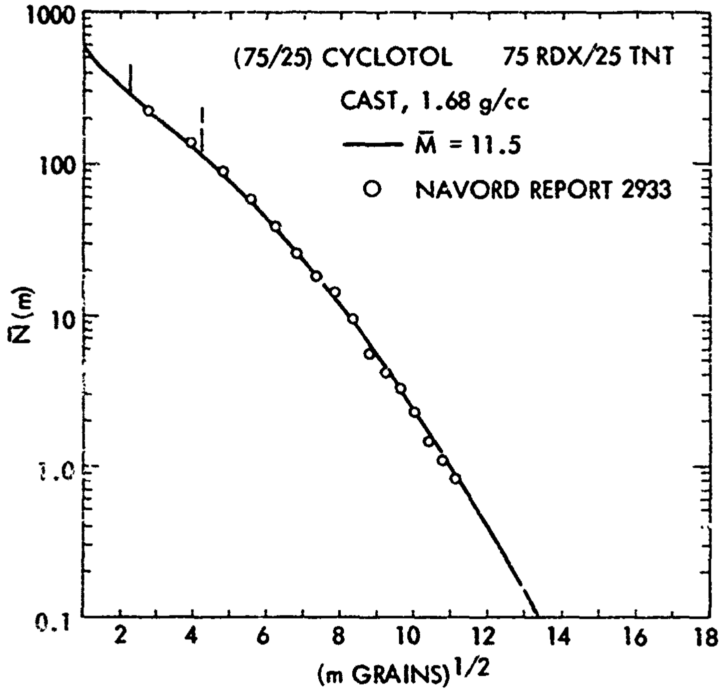

FIG. 8-3

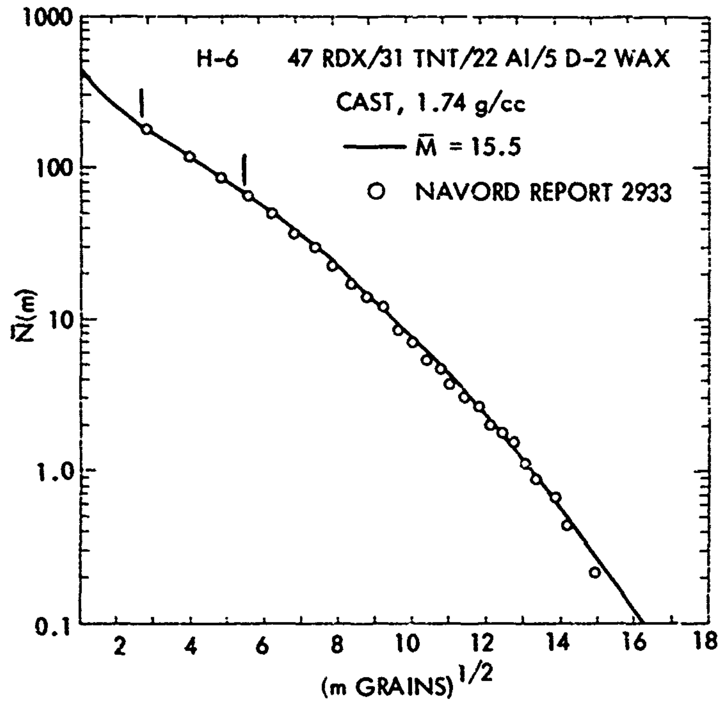

FIG. 8-4

FIG. 8 CUMULATIVE FRAGMENT WEIGHT DISTRIBUTION (2 IN. ID - 2.5 IN. OD CYLINDER FRAGMENTATION TEST) (CONT.)

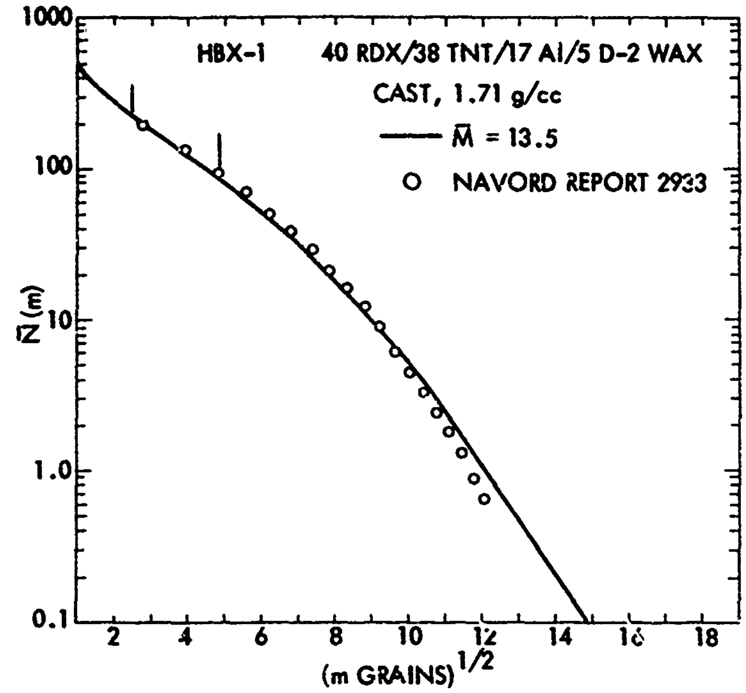

FIG. 8-5

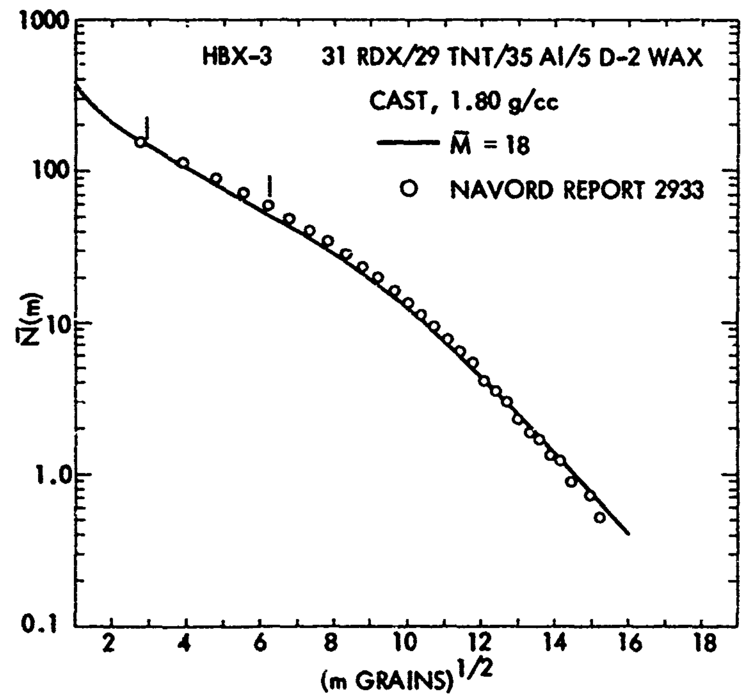

FIG. 8-6

FIG. 8 CUMULATIVE FRAGMENT WEIGHT DISTRIBUTION (2 IN. ID - 2.5 IN. OD CYLINDER FRAGMENTATION TEST) (CONT.)

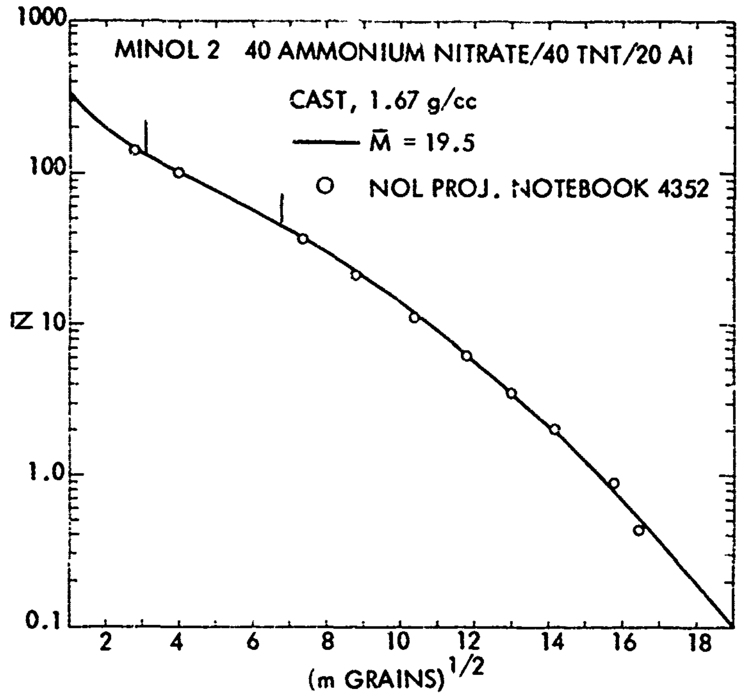

FIG. 8-7

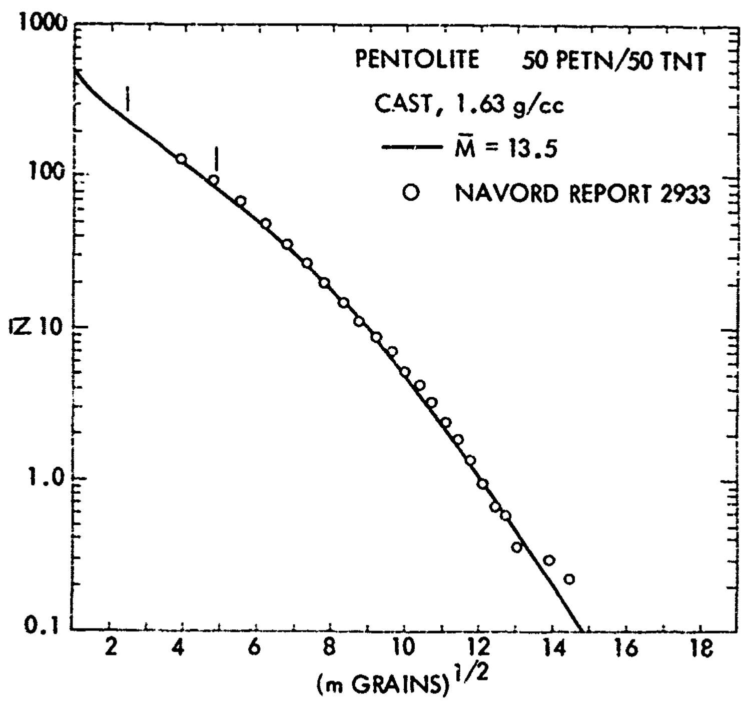

FIG. 8-8

FIG. 8 CUMULATIVE FRAGMENT WEIGHT DISTRIBUTION (2 IN. ID - 2.5 IN. OD CYLINDER FRAGMENTATION TEST) (CONT.)

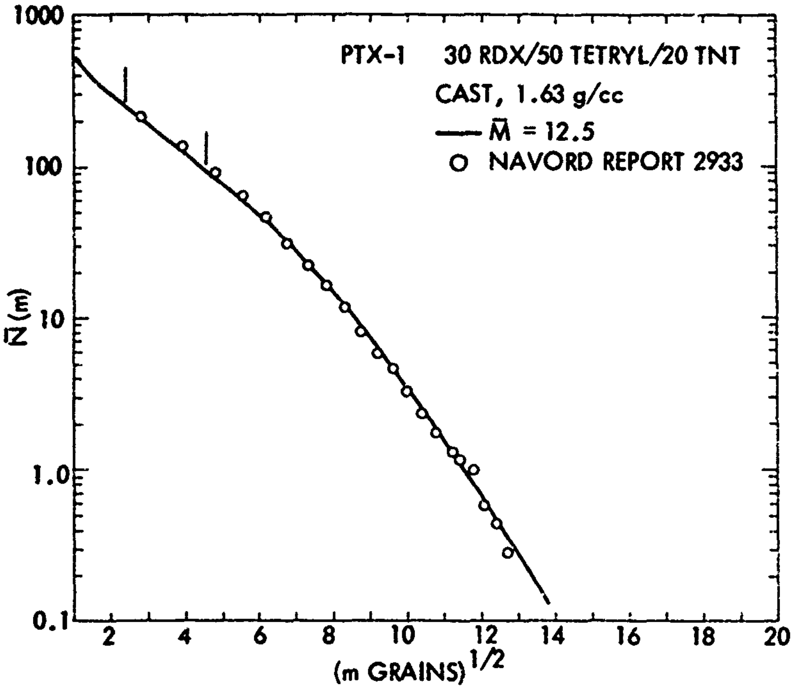

FIG. 8-9

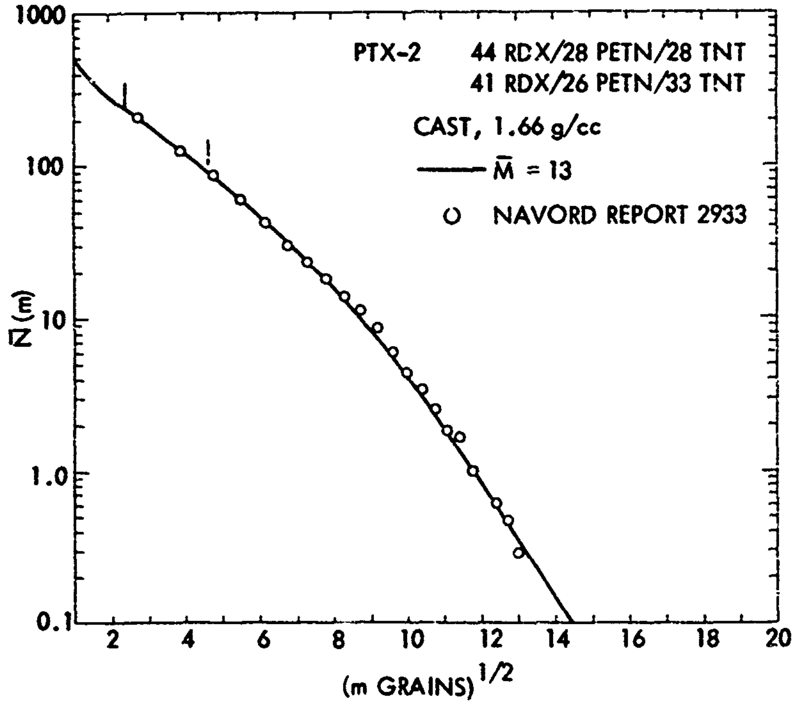

FIG. 8-10

FIG. 8 CUMULATIVE FRAGMENT WEIGHT DISTRIBUTION (2 IN. ID - 2.5 IN. OD CYLINDER FRAGMENTATION TEST) (CONT.)

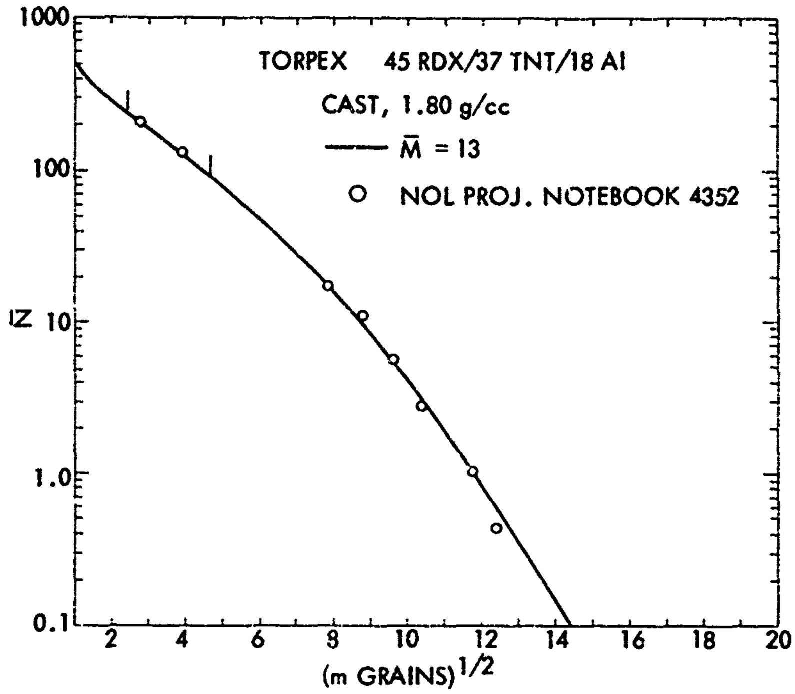

FIG. 8-11

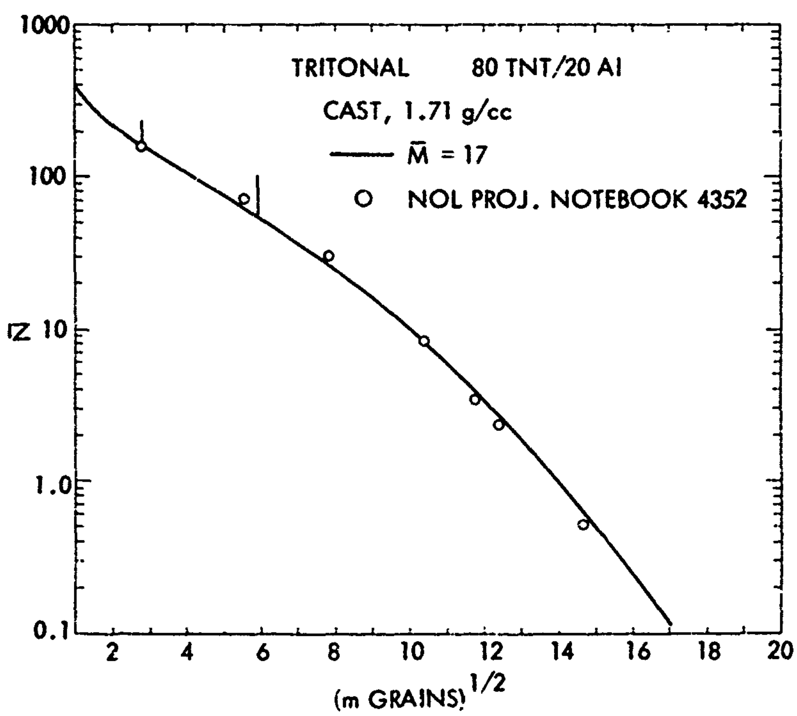

FIG. 8-12

FIG. 8 CUMULATIVE FRAGMENT WEIGHT DISTRIBUTION (2 IN. ID - 2.5 IN. OD CYLINDER FRAGMENTATION TEST) (CONT.)

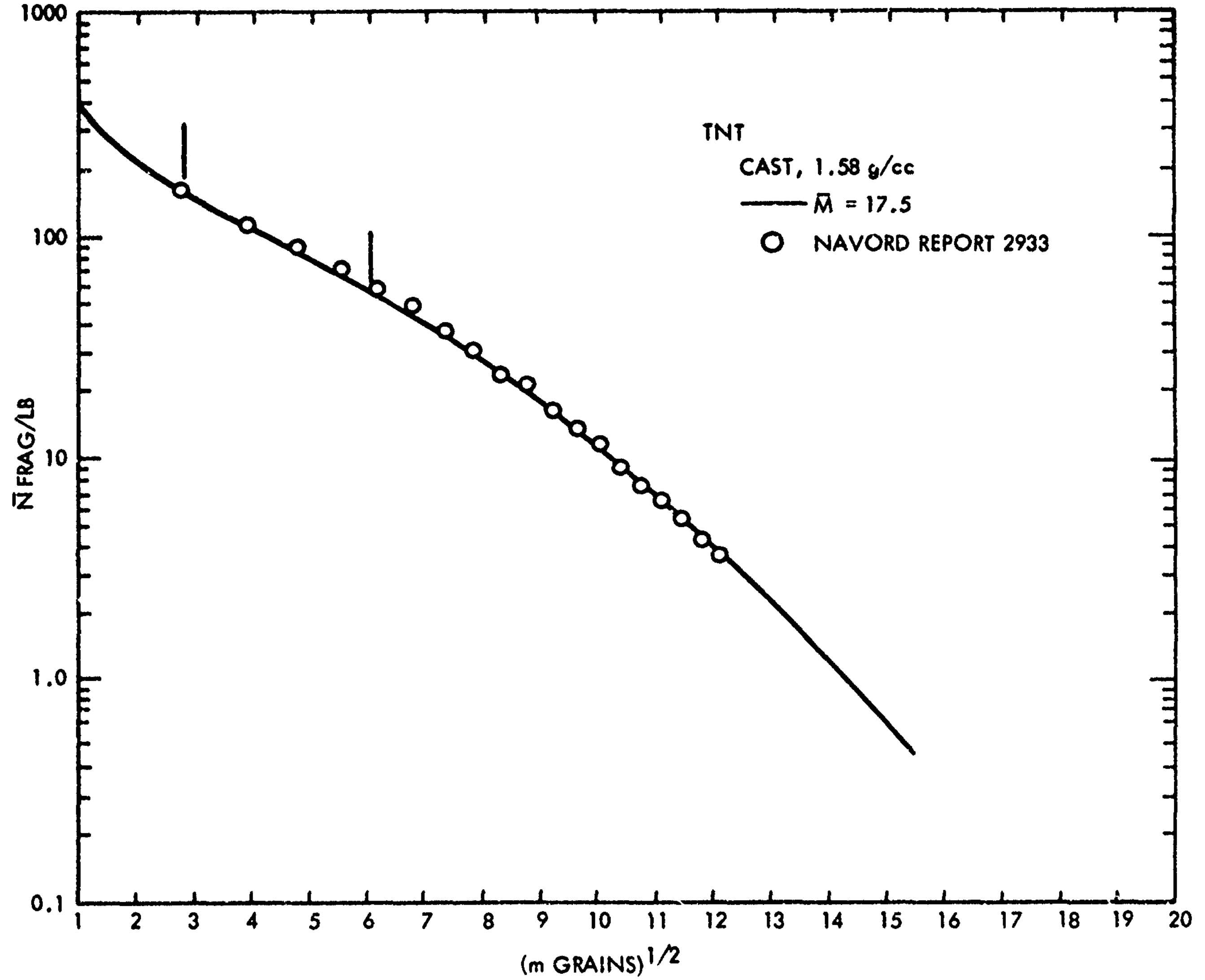

FIG. 8-13

FIG. 8 CUMULATIVE FRAGMENT WEIGHT DISTRIBUTION (2 IN. ID - 2.5 IN. OD CYLINDER FRAGMENTATION TEST) (CONT.)

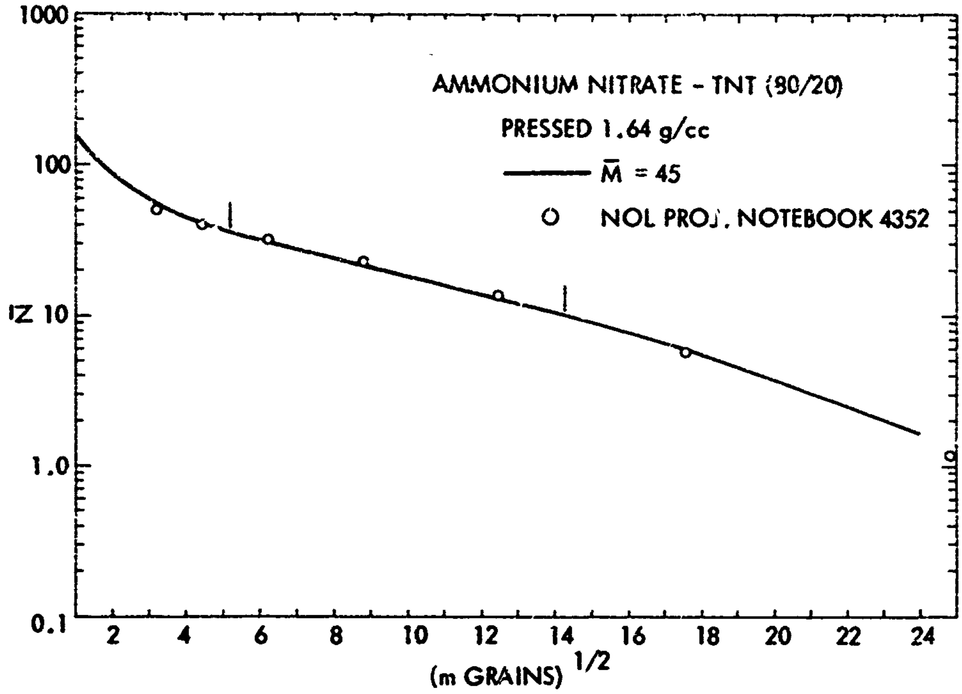

FIG. 8-14

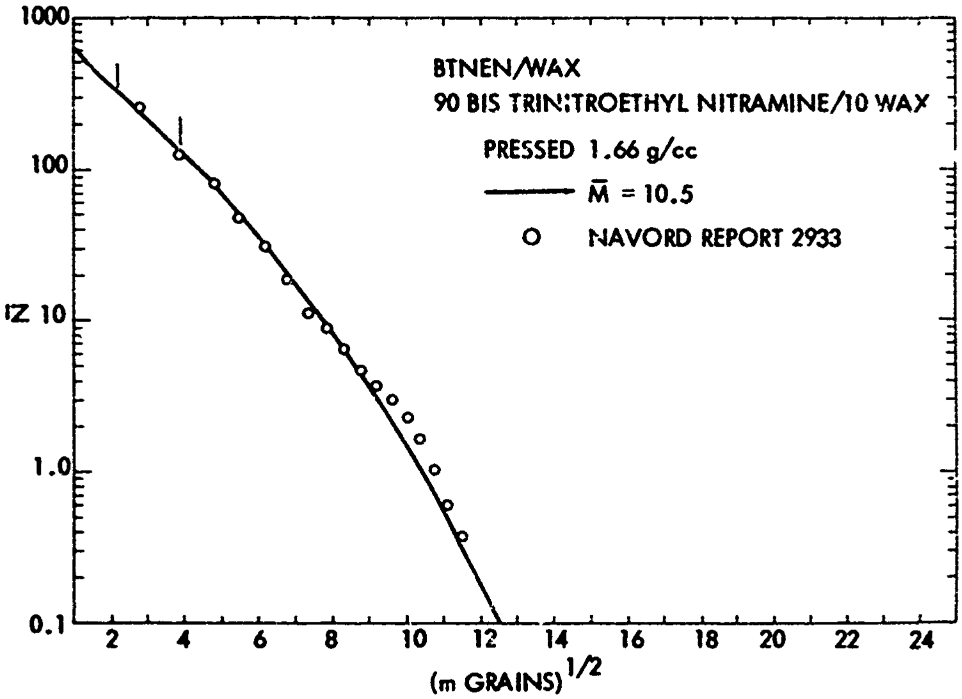

FIG. 8-15

FIG. 8 CUMULATIVE FRAGMENT WEIGHT DISTRIBUTION (2 IN. ID - 2.5 IN. OD CYLINDER FRAGMENTATION TEST) (CONT.)

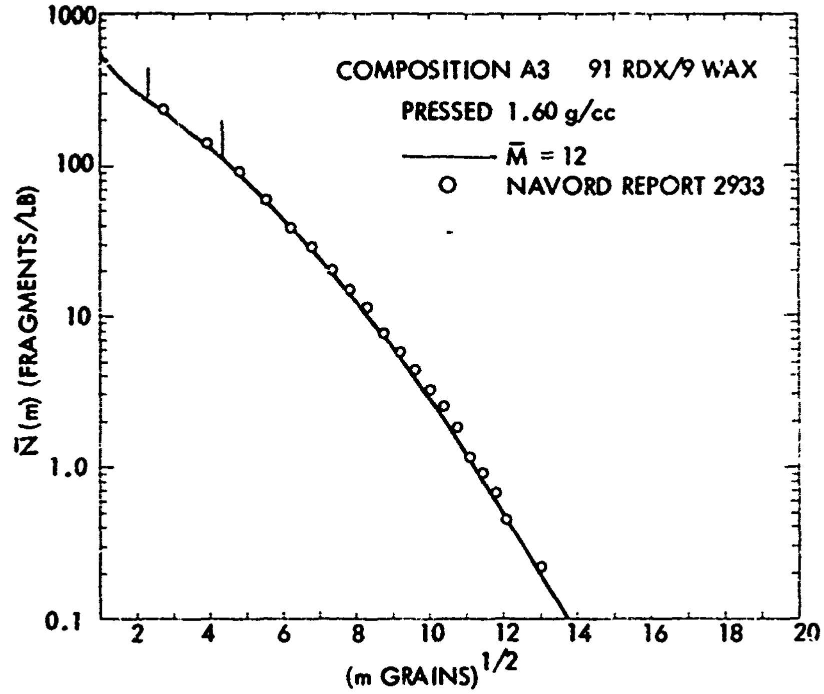

FIG. 8-16

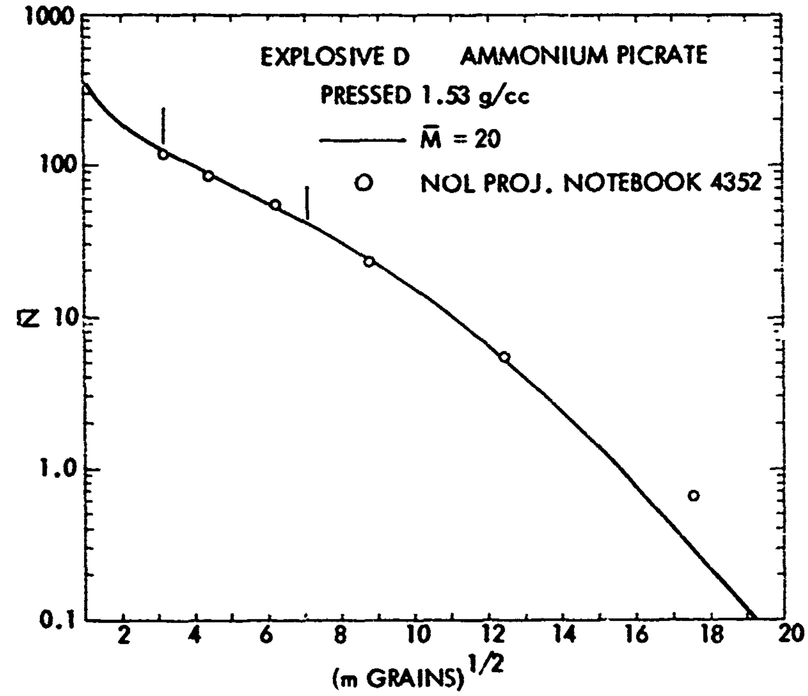

FIG. 8-17

FIG. 8 CUMULATIVE FRAGMENT WEIGHT DISTRIBUTION (2 IN. ID - 2.5 IN. OD CYLINDER FRAGMENTATION TEST) (CONT.)

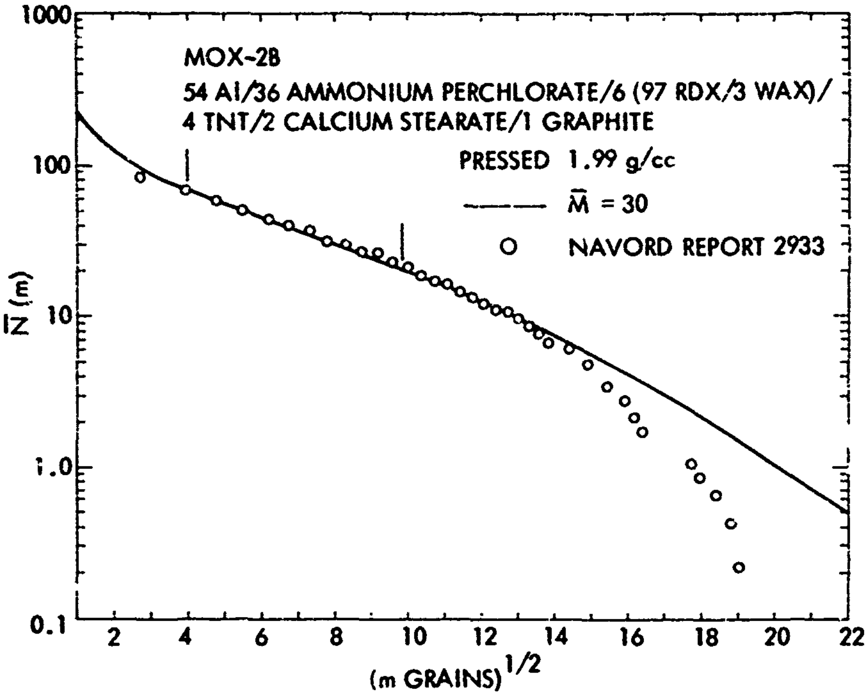

FIG. 8-18

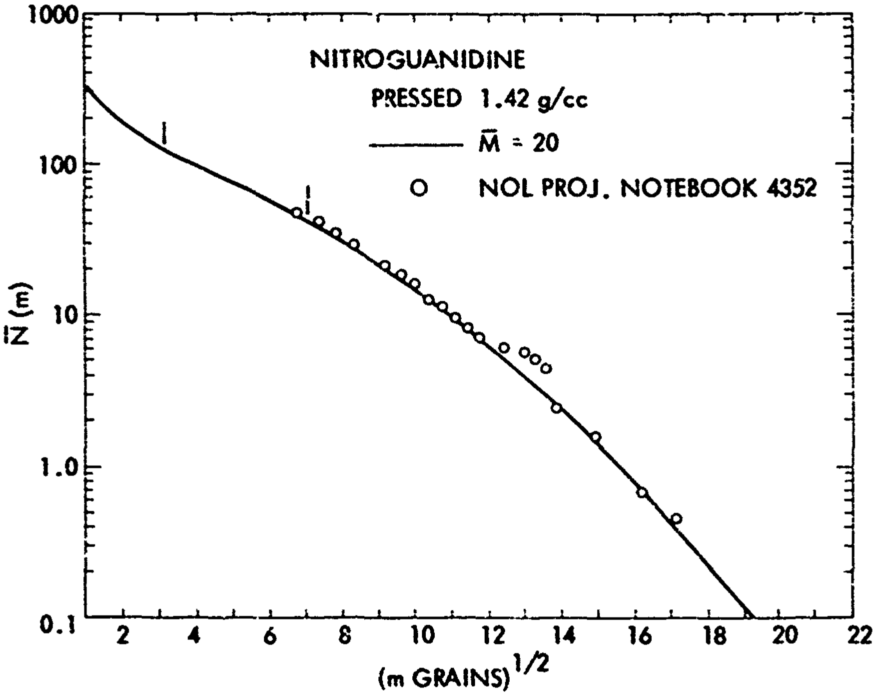

FIG. 8-19

FIG. 8 CUMULATIVE FRAGMENT WEIGHT DISTRIBUTION (2 IN. ID - 2.5 IN. OD CYLINDER FRAGMENTATION TEST) (CONT.)

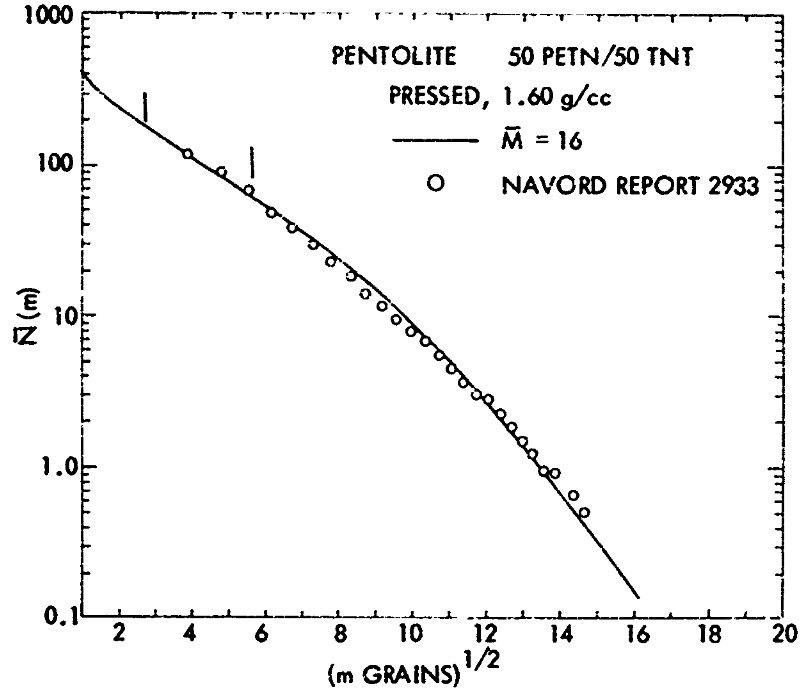

FIG. 8-20

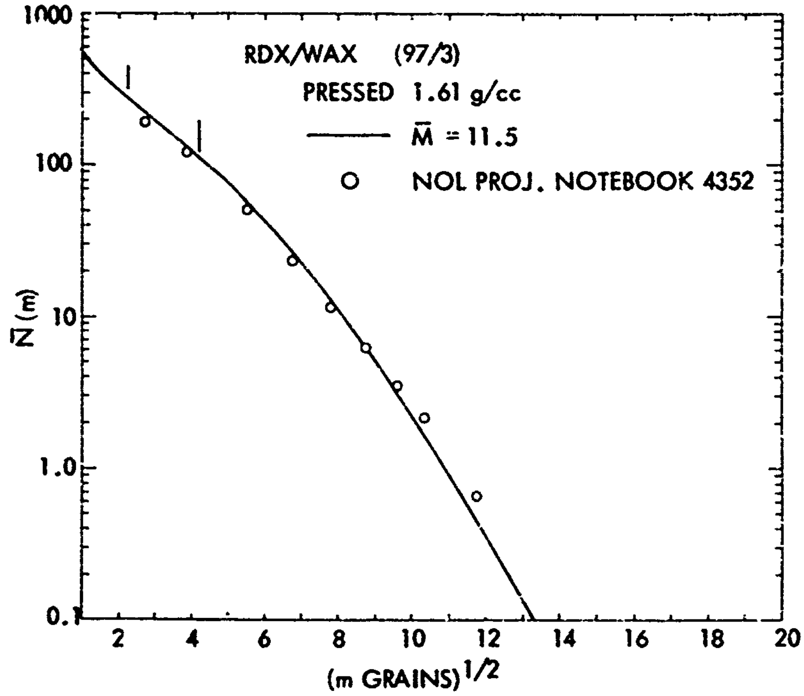

FIG. 8-21

FIG. 8 CUMULATIVE FRAGMENT WEIGHT DISTRIBUTION (2 IN. ID - 2.5 IN. OD CYLINDER FRAGMENTATION TEST) (CONT.)

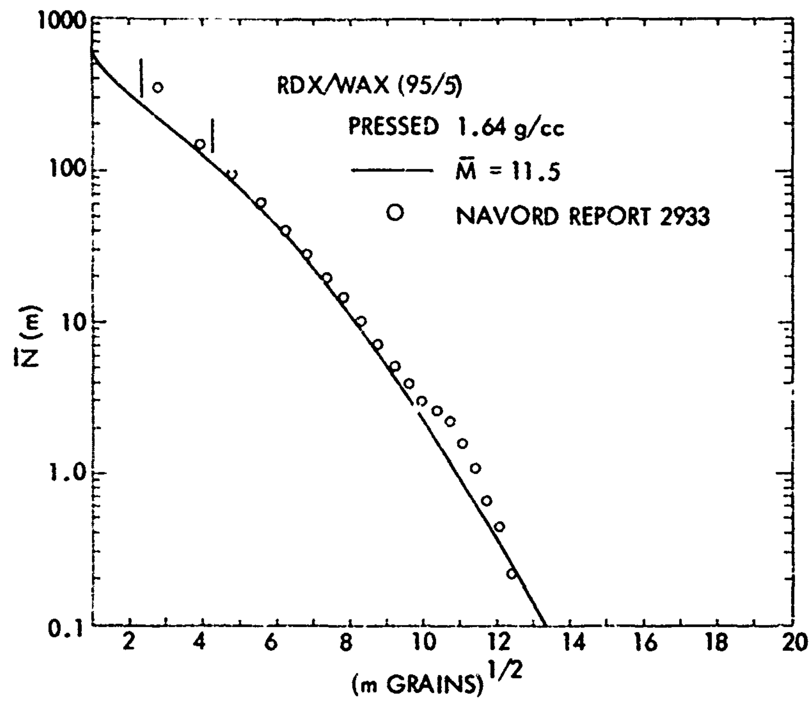

FIG. 8-22

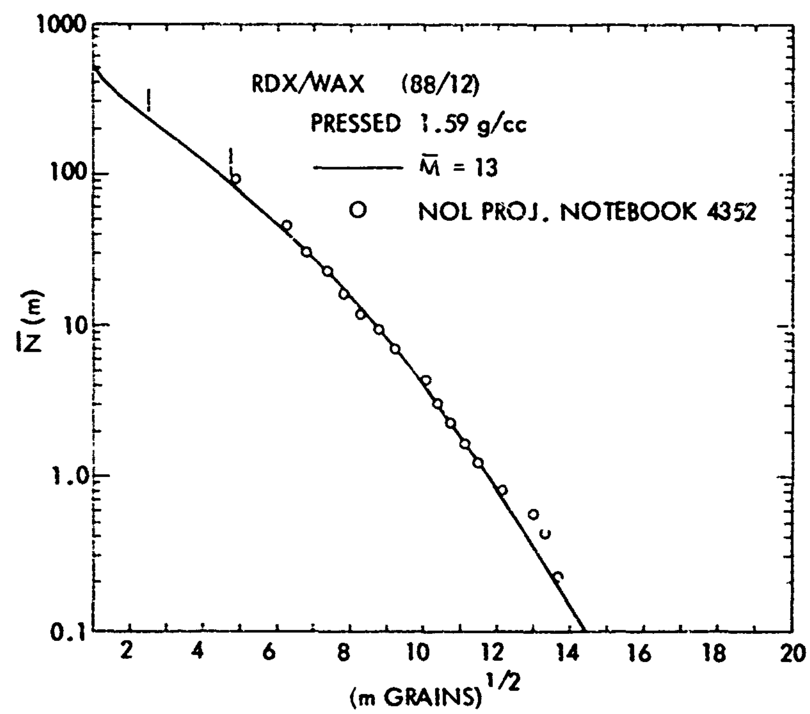

FIG. 8-23

FIG. 8 CUMULATIVE FRAGMENT WEIGHT DISTRIBUTION (2 IN. ID - 2.5 IN. OD CYLINDER FRAGMENTATION TEST) (CONT.)

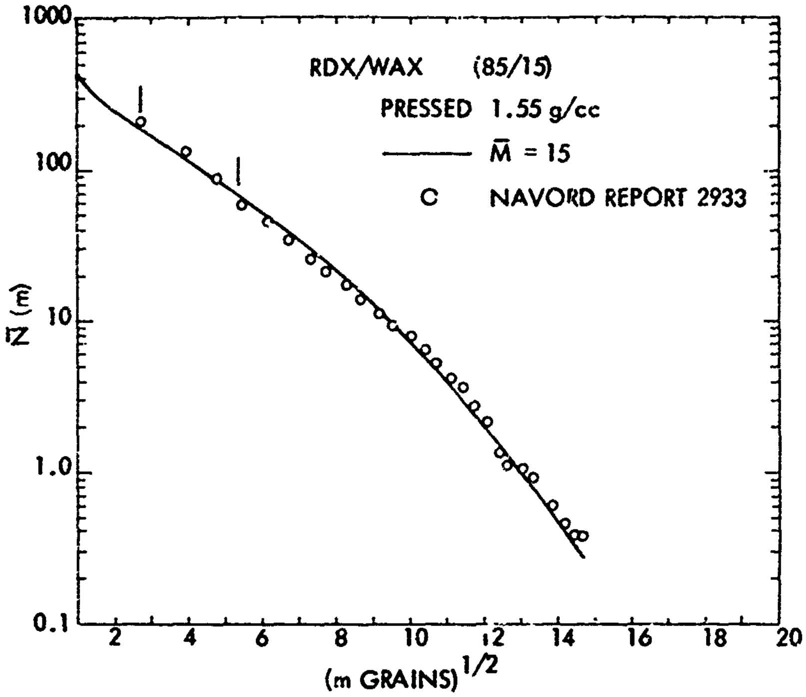

FIG. 8-24

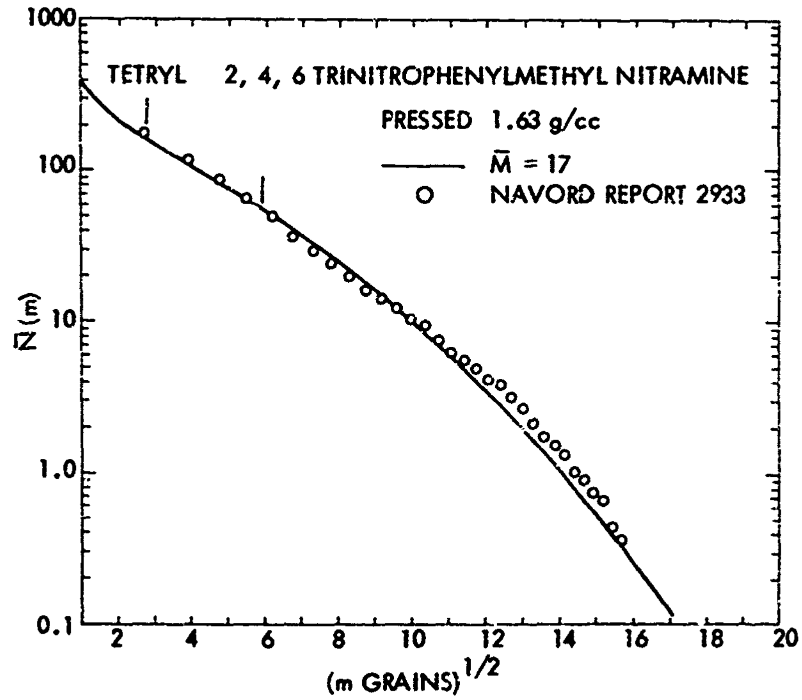

FIG. 8-25

FIG. 8 CUMULATIVE FRAGMENT WEIGHT DISTRIBUTION (2 IN. ID - 2.5 IN. OD CYLINDER FRAGMENTATION TEST) (CONT.)

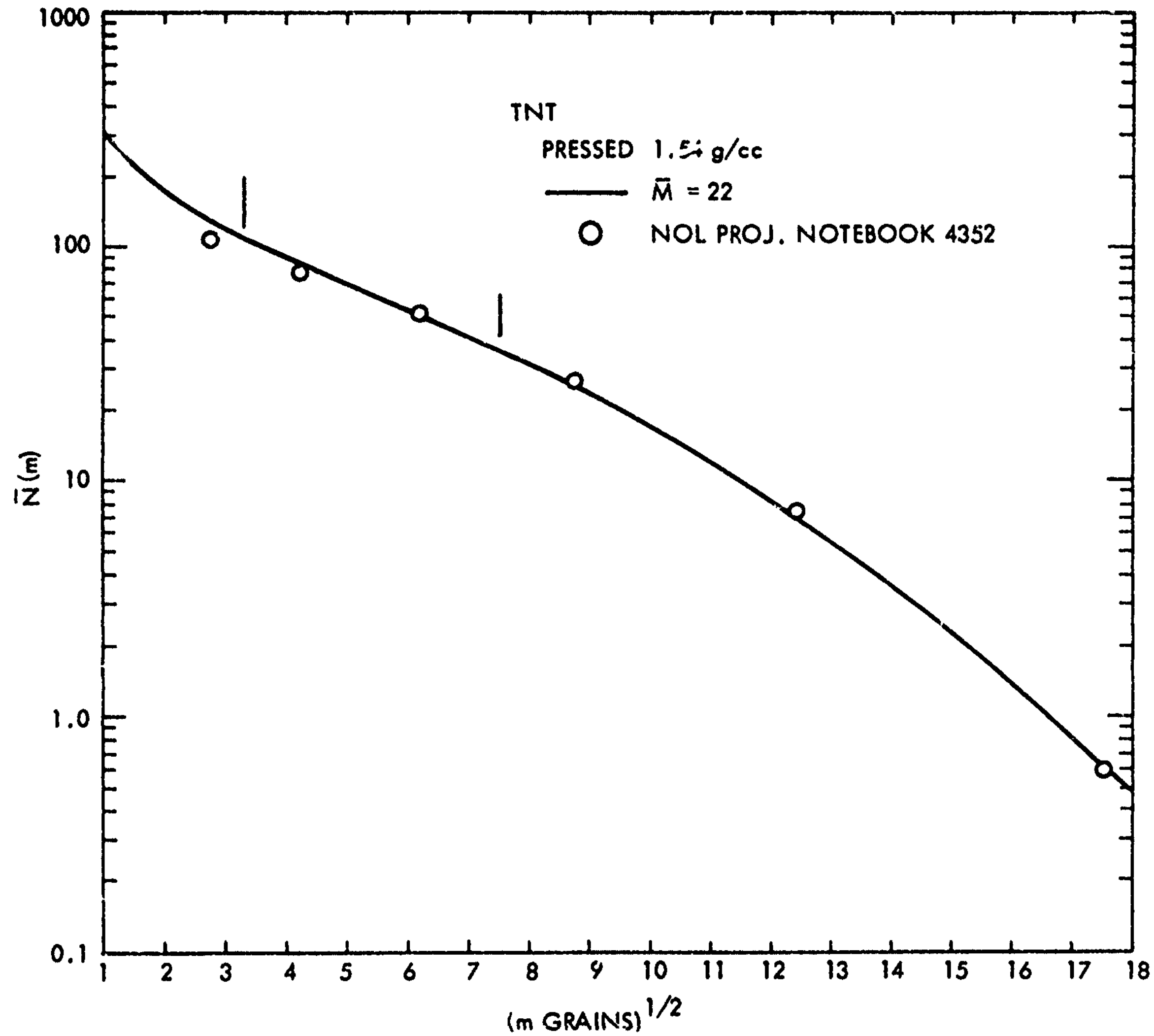

FIG. 8-26

FIG. 8 CUMULATIVE FRAGMENT WEIGHT DISTRIBUTION (2 IN. ID - 2.5 IN. OD CYLINDER FRAGMENTATION TEST) (CONT.)

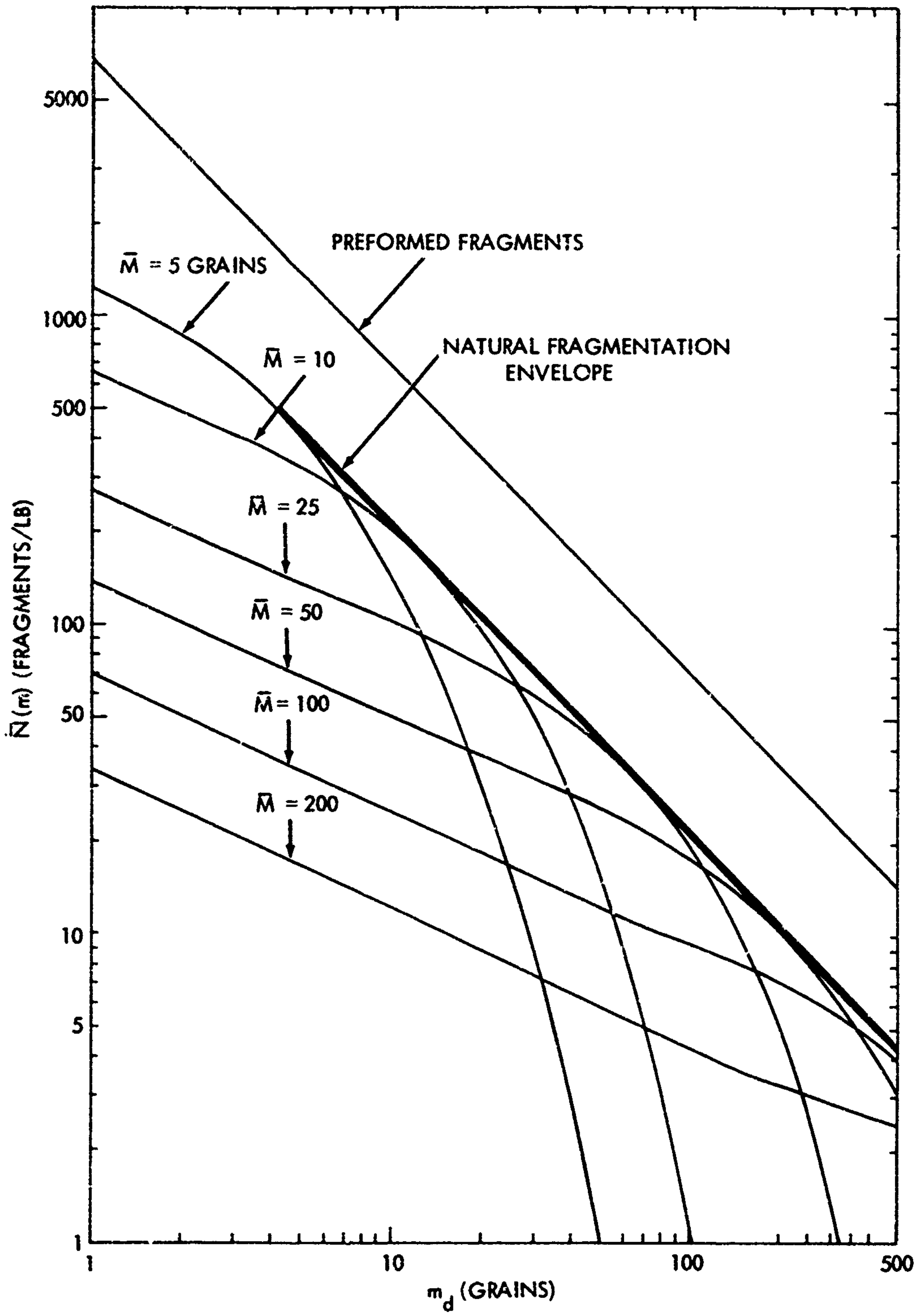

FIG. 9 CUMULATIVE FRAGMENTS PER LB. VS DESIGN WEIGHT

TABLE I

LIST-BASIC COMPUTER PROGRAM FOR FRAGMENT WEIGHT DISTRIBUTION CALCULATION

```
45    DIM M(30)
50    M(1)=1
52    M(2)=1.5
54    M(3)=2
56    M(4)=3
58    M(5)=4
60    M(6)=5
62    M(7)=7
64    M(8)=10
66    M(9)=20
68    M(10)=30
70    M(11)=50
72    M(12)=75
74    M(13)=100
76    M(14)=150
78    M(15)=200
80    M(16)=240
82    M(17)=480
95    REM FSQ034  CALCULATES NB VS MBAR
96    FØR K3=4 TØ 50
97    C=0.2364
98    B2=1.77
99    L=2050/7000
100   M1=K3
110   B1=C/4
117   LET U2=B1*M1↑B2
120   LET K=.6
140   LET M2=1+(2/9)*(M1-1)↑(5/4)
153   LET M4=4*U2
155   M3=M4
160   N6=L/4/U2
162   N3=N6
164   N7=N3*EXP((M3/U2)**.5)
170   N2=N7*EXP(-(M2/U2)**.5)
190   LET N1=1/(M1+K)
200   LET P=LØG(N2/N1)/LØG(M2)
210   LET B=1+1/P
220   LET R1=N1*(1-(N2/N1)↑B)/B
230   LET S1=N2*(M2+2*(M2*U2)↑.5+2*U2)
240   LET S2=N3*(M3+2*(M3*U2)↑.5+2*U2)
250   LET R2=S1-S2
260   LET R3=M1/(M1+K)-R1-R2
265   GØSUB 1000
267   U3=(2*Q*U2**.5*M3**(Q-.5))**(1/Q)
269   N8=N3*EXP((M3/U3)**Q)
272   PRINT"MBAR="M1
275   PRINT"K="K,"N1B="L*7000
278   PRINT"ME="M4,"NEB="N6*7000
280   PRINT"M2="M2,"M3="M3
282   PRINT"SQR(M2)="SQR(M2),"SQR(M3)="SQR(M3)
285   PRINT"MU2="U2,"SQR(MU2)="U2↑.5
287   PRINT"N2B="N2*7000,"N3B="N3*7000
288   PRINT "Q="Q
290   PRINT"MU3="U3
291   PRINT"ESN2="N7,"ESN3="N8
292   PRINT"W1/WT="R1,"W2/WT="R2,"W3/WT="R3
```

TABLE I (CONT.)

```
294   PRINT "(WT-W(1))/WT="K/(M1+K)
296   PRINT
298   PRINT"M","SQR(M)","NB"
300   FØR K2=1 TØ 17
305   M=M(K2)
310   IF M<M2 THEN 500
320   IF M<M3 THEN 600
330   N=N8*EXP(-(M/U3)**Q)
340   GØ TØ 700
500   LET N=N1*M↑P
510   GØ TØ 700
600   N=N7*EXP(-(M/U2)**.5)
700   PRINT M,SQR(M),N*7000
710   NEXT K2
720   NEXT K3
725   GØ TØ 9999
1000  A=.2
1010  LET F4=0
1020  Q1=.5
1030  Q2=1.5
1040  LET R=Q1
1050  GØSUB1500
1060  LET F1=F
1070  LET R=Q2
1080  GØSUB 1500
1090  LET F2=F
1100  LET Q3=Q1+(Q2-Q1)*ABS(F1)/(ABS(F1)+ABS(F2))
1110  GØSUB 1500
1120  LET F3=F
1150  IF ABS(F4-F3)<1E-7 THEN 1300
1154  IFABS(F3)<1E-5 THEN 1300
1160  LET F4=F3
1170  PRINT
1180  LET Q5=Q3-A*(Q2-Q1)
1190  LET Q2=Q3+A*(Q2-Q1)
1200  LET Q1=Q5
1210  GØ TØ 1040
1300  LETQ=Q3
1305  PRINT
1310  RETURN
1500  LET U3=(2*R*U2↑.5*M3↑(R-.5))↑(1/R)
1510  LET Y=EXP((M3/U3)↑R)
1512  LET Y=Y*N3
1515  LET H=N3/Y/100
1520  S=0
1530  FØR J=1 TØ 100 STEP 1
1540  F=(-LØG(J*H))↑(1/R)
1550  IF J=100 THEN1590
1560  IF ABS(INT(J/2)-J/2)<.1 THEN 1610
1570  LET S=S+4*F
1580  GØ TØ 1620
1590  LET S=S+F
1600  GØ TØ 1620
1610  LET S=S+2*F
1620  NEXT J
1630  LET F=H*S*Y*U3/3-R3
1640  RETURN
9999  END
```

TABLE II

Computer Program Outline

INPUT

Specify values of $\overline{M}$ and m for which $\overline{N}(m)$ are to be calculated. Insert constants L, C, B_2, and K.

CALCULATION PROCEDURE

→For specified values of $\overline{M}$

Calculate listed parameters

Program Name	Text Name	Equation in Text
U2	μ_{II}	19
M2	m_2	32
M4	$m_e (=m_3)$	18
N6	$N_e (=N_3)$	20
N7	n_{II}	21
N2	N_2	12
N1	N_1	12
P	p	23
R1, R2, R3	W_I, W_{II}, W_{III}	26-28
Q	q	24-29
U3	μ_{III}	25
N8	n_{III}	24

Print parameter values

→For specified values of m

Calculate $\overline{N}(m)$ — 6,7, or 8

Print m, $m^{1/2}$, $\overline{N}(m)$

→Next m

→Next $\overline{M}$

TABLE III

REGION BOUNDARY AND ENVELOPE POINTS FOR VARIOUS VALUES OF $\bar{M}$

$\bar{M}$ (GRAINS)	m_1 (GRAINS)	m_2 (GRAINS)	m_3 (GRAINS)	$N(m_3)$ (FRAGMENTS/GRAIN)
4	1	1.87738	2.74975	.106503
5	1	2.25708	4.08154	7.17516E-2
6	1	2.6615	5.63605	5.19614E-2
7	1	3.08678	7.40408	3.95535E-2
8	1	3.53023	9.37814	3.12276E-2
9	1	3.98985	11.552	2.53512E-2
10	1	4.4641	13.9203	2.10382E-2
11	1	4.95173	16.4783	1.77723E-2
12	1	5.45173	19.222	1.52355E-2
13	1	5.96323	22.1476	.013223
14	1	6.48551	25.2519	1.15974E-2
15	1	7.01794	28.5318	1.02642E-2
16	1	7.55997	31.9845	9.15621E-3
17	1	8.11111	35.6075	8.22458E-3
18	1	8.67094	39.3985	7.43320E-3
19	1	9.23907	43.3552	6.75433E-3
20	1	9.81515	47.4756	6.16858E-3
22	1	10.9899	56.1999	5.21099E-3
24	1	12.193	65.5573	4.46719E-3
26	1	13.4226	75.5354	3.87709E-3
28	1	14.677	86.1226	3.40047E-3
30	1	15.955	97.3088	3.00957E-3
32	1	17.2551	109.084	2.68468E-3
34	1	18.5764	121.441	2.41152E-3
36	1	19.9179	134.37	2.17948E-3
38	1	21.2787	147.865	1.98058E-3
40	1	22.658	161.917	1.80868E-3
45	1	[illegible]1828	199.45	1.46833E-3
50	1	[illegible].093	240.339	1.21852E-3
55	1	3[illegible]297	284.505	1.02936E-3
60	1	[illegible]3373	331.875	8.82431E-4
65	1	[illegible].2265	382.388	7.65864E-4
70	1	45.1925	435.984	6.71715E-4
75	1	49.2311	492.613	5.94497E-4
80	1	53.3385	552.226	5.30321E-4
85	1	57.5115	614.779	4.76362E-4
90	1	61.747	680.231	4.30526E-4
95	1	66.0425	748.546	3.91235E-4
100	1	70.3955	819.686	3.57280E-4
110	1	79.2655	970.315	3.01817E-4
120	1	88.3416	1131.87	2.58736E-4
130	1	97.6106	1304.15	2.24558E-4
140	1	107.061	1486.94	1.96953E-4
150	1	116.683	1680.08	1.74312E-4
160	1	126.468	1883.39	1.55495E-4
170	1	136.408	2096.73	1.39673E-4
180	1	146.497	2319.96	1.26234E-4
190	1	156.727	2552.94	1.14713E-4
200	1	167.094	2795.57	1.04758E-4

TABLE IV

CALCULATED VALUES OF PARAMETERS p, n_{II}, μ_{II}, AND N_2

$\bar{M}$ (GRAINS)	p	n_{II} (GRAINS)	μ_{II} (GRAINS)	N_2 (FRAGMENTS/GRAIN)
4	-.531214	.786957	.687438	.150747
5	-.490195	.530176	1.02039	.119813
6	-.454148	.383946	1.40901	9.71372E-2
7	-.437672	.292263	1.85102	8.03421E-2
8	-.429512	.230743	2.34454	6.76416E-2
9	-.425328	.187322	2.888	5.78262E-2
10	-.423212	.155452	3.43007	5.00863E-2
11	-.422237	.13132	4.11958	4.38723E-2
12	-.421919	.112576	4.8055	3.88036E-2
13	-.421993	9.77052E-2	5.53691	.034611
14	-.422302	8.56941E-2	6.31298	3.11001E-2
15	-.422754	.075843	7.13295	2.81279E-2
16	-.423292	6.76558E-2	7.99613	2.55871E-2
17	-.42388	6.07719E-2	8.90189	2.33963E-2
18	-.424494	5.49244E-2	9.84963	2.14923E-2
19	-.425119	4.99118E-2	10.8388	1.98261E-2
20	-.425745	.04558	11.8689	1.83585E-2
22	-.426978	3.85043E-2	14.05	1.59005E-2
24	-.428164	3.30083E-2	16.3893	1.39326E-2
26	-.429293	.028648	18.8838	1.23295E-2
28	-.430362	2.51262E-2	21.5307	1.10042E-2
30	-.431373	2.22378E-2	24.3272	9.89422E-3
32	-.432329	1.98373E-2	27.2711	8.95420E-3
34	-.433234	1.78188E-2	30.3602	8.15016E-3
36	-.434092	1.61043E-2	33.5925	7.45638E-3
38	-.434906	1.46346E-2	36.9662	6.85301E-3
40	-.435681	1.33645E-2	40.4794	6.32455E-3
45	-.437464	1.08495E-2	49.8625	5.25660E-3
50	-.439059	9.00369E-3	60.0848	4.45165E-3
55	-.440501	7.60598E-3	71.1262	.003828
60	-.441315	6.52033E-3	82.9689	3.33373E-3
65	-.44302	5.65901E-3	95.597	2.93454E-3
70	-.444133	4.96334E-3	108.996	2.60691E-3
75	-.445166	4.39277E-3	123.153	2.33427E-3
80	-.446129	3.91857E-3	138.056	2.10466E-3
85	-.447031	3.51986E-3	153.695	1.90925E-3
90	-.447878	3.18118E-3	170.058	1.74138E-3
95	-.448678	2.89036E-3	187.136	1.59598E-3
100	-.449434	2.63996E-3	204.921	1.46911E-3
110	-.450832	2.23014E-3	242.579	1.25915E-3
120	-.452102	1.91182E-3	282.969	1.09342E-3
130	-.453264	1.65927E-3	326.037	9.60039E-4
140	-.454335	1.45529E-3	371.[illegible]36	8.50908E-4
150	-.455326	.001288	420.019	7.60346E-4
160	-.45625	1.14896E-3	470.847	6.84267E-4
170	-.457113	1.03205E-3	524.182	6.19665E-4
180	-.457924	9.32749E-4	579.989	5.64284E-4
190	-.458687	8.47624E-4	638.236	5.16407E-4
200	-.459409	7.74059E-4	698.893	4.74702E-4

TABLE V

CALCULATED VALUES OF PARAMETERS n_{III}, μ_{III}, AND q

$\overline{M}$ (GRAINS)	n_{III} (GRAINS)	μ_{III} (GRAINS)	q
4	.588015	1.10108	.585282
5	.338579	2.06463	.644517
6	.219969	3.32018	.693007
7	.154941	4.8394	.73239
8	.115506	6.60063	.764517
9	8.97608E-2	8.58769	.790938
10	7.19925E-2	10.7882	.812861
11	5.91875E-2	13.1922	.831207
12	4.96358E-2	15.7917	.846681
13	4.23081E-2	18.58	.859827
14	3.65545E-2	21.5511	.871064
15	3.19476E-2	24.7	.880722
16	2.81969E-2	28.0221	.889065
17	2.50989E-2	31.5133	.8963
18	.022508	35.1699	.902598
19	2.03171E-2	38.9885	.908097
20	1.84464E-2	42.9659	.91291
22	1.54365E-2	51.3856	.920841
24	1.31384E-2	60.408	.926974
26	1.13403E-2	70.0146	.931727
28	9.90431E-3	80.1887	.935403
30	8.73759E-3	90.9155	.938229
32	7.77541E-3	102.181	.940377
34	6.97167E-3	113.974	.941976
36	6.29266E-3	126.282	.943131
38	5.71330E-3	139.095	.943922
40	5.21457E-3	152.403	.944413
45	4.23220E-3	187.781	.944644
50	3.51519E-3	226.073	.943877
55	2.97422E-3	267.168	.942466
60	2.55494E-3	310.972	.94064
65	2.22271E-3	357.402	.938548
70	1.95448E-3	406.383	.936289
75	1.73447E-3	457.847	.933931
80	1.55153E-3	511.735	.931521
85	1.39758E-3	567.99	.929093
90	1.26666E-3	626.562	.92667
95	1.15430E-3	687.405	.924266
100	1.05706E-3	750.475	.921894
110	8.97855E-4	883.136	.917273
120	7.73783E-4	1024.26	.91284
130	6.75003E-4	1173.59	.908609
140	5.94933E-4	1330.9	.90458
150	5.29026E-4	1495.99	.900746
160	4.74052E-4	1668.67	.897099
170	4.27666E-4	1848.78	.893627
180	3.88125E-4	2036.16	.890321
190	3.54114E-4	2230.67	.887169
200	3.24623E-4	2432.18	.884161

TABLE VI

CALCULATED WEIGHT FRACTIONS IN VARIOUS REGIONS

$\bar{M}$ (GRAINS)	1-W(1)	W_I	W_{II}	W_{III}
4	.130435	9.10696E-2	.100636	.67786
5	.107143	8.83233E-2	.146453	.658081
6	9.09091E-2	8.90368E-2	.176338	.643716
7	7.89474E-2	9.06119E-2	.197374	.633067
8	6.97674E-2	9.22368E-2	.213024	.624972
9	.0625	9.36638E-2	.225162	.618674
10	5.66038E-2	9.48362E-2	.234885	.613675
11	5.17241E-2	9.57633E-2	.242872	.609641
12	.047619	9.64741E-2	.24957	.606337
13	4.41176E-2	9.70013E-2	.255283	.603599
14	4.10959E-2	9.73752E-2	.260223	.601306
15	3.84615E-2	.097622	.264547	.59937
16	3.61446E-2	9.77638E-2	.26837	.597722
17	3.40909E-2	9.78189E-2	.271779	.596311
18	3.22581E-2	9.78025E-2	.274843	.595097
19	3.06122E-2	9.77267E-2	.277615	.594046
20	2.91262E-2	.097602	.280137	.593135
22	2.65487E-2	9.72377E-2	.284566	.591648
24	2.43902E-2	9.67611E-2	.288338	.590511
26	2.25564E-2	9.62081E-2	.291598	.589637
28	.020979	9.56038E-2	.294451	.588966
30	1.96078E-2	.094966	.296973	.588453
32	1.84049E-2	9.43076E-2	.299223	.588064
34	.017341	9.36379E-2	.301246	.587776
36	1.63934E-2	9.29636E-2	.303075	.587568
38	.015544	9.22897E-2	.304741	.587425
40	1.47783E-2	9.16197E-2	.306265	.587337
45	1.31579E-2	8.99775E-2	.309569	.587296
50	1.18577E-2	8.83987E-2	.31231	.587434
55	1.07914E-2	8.68926E-2	.314629	.587687
60	9.90099E-3	8.54613E-2	.316621	.588017
65	9.14634E-3	8.41029E-2	.318356	.588395
70	8.49858E-3	8.28142E-2	.319882	.588805
75	7.93651E-3	8.15909E-2	.321238	.589234
80	7.44417E-3	8.04286E-2	.322452	.589675
85	7.00935E-3	7.93231E-2	.323547	.590121
90	6.62252E-3	7.82702E-2	.32454	.590567
95	6.27615E-3	7.72661E-2	.325446	.591012
100	5.96421E-3	7.63073E-2	.326277	.591452
110	5.42495E-3	7.45127E-2	.327748	.592315
120	4.97512E-3	7.28636E-2	.329013	.593148
130	4.59418E-3	7.13411E-2	.330116	.593949
140	4.26743E-3	6.99295E-2	.331086	.594717
150	3.98406E-3	6.86154E-2	.331948	.595453
160	3.73599E-3	6.73877E-2	.33272	.596157
170	.003517	.066237	.333416	.59683
180	3.32226E-3	6.51552E-2	.334047	.597476
190	3.14795E-3	6.41355E-2	.334622	.598094
200	2.99103E-3	6.31717E-2	.33515	.598[illegible]

TABLE VII

Average weight of fragments weighing more than one grain from steel cylinders* filled with various cast explosives**

Explosive	Composition (parts by weight)	Density (g/cc)	Detonation Velocity (m/sec)	$\overline{M}$ (grains)
Baratol	77 Barium Nitrate/23 TNT/0.1 Nitrocellulose	2.49	4900	30
Composition B	59.5 RDX/39.5 TNT/1 Wax	1.68	7900	12
75/25 Cyclotol	Any RDX-TNT combination, in this case 75 RDX/25 TNT	1.69	8070	11.5
H-6	47 RDX/31 TNT/22 Al/5 D-2 Wax	1.73	7460	15.5
HBX-1	40 RDX/38 TNT/17 Al/5 D-2 Wax	1.71	7440	13.5
HBX-3	31 RDX/29 TNT/35 Al/5 D-2 Wax	1.81	7108	18
Minol 2	40 Ammonium Nitrate/40 TNT/20 Al	1.67		19.5
Pentolite	50 PETN/50 TNT	1.64	7530	13.5
PTX-1	30 RDX/50 Tetryl/20 TNT	1.64	7730	12.5
PTX-2	44 RDX/28 PETN/28 TNT 41 RDX/26 PETN/33 TNT	1.67	7930	13
Torpex	45 RDX/37 TNT/18 Al	1.80		13
Tritonal	80 TNT/20 Al	1.71		17
TNT	Trinitrotoluene	1.58	6880	17.5

*9" long, 2" I.D., 2.5" O.D., AISI 1045 seamless, cold rolled, stress relief annealed, Rockwell hardness approximately 100-B.

**See Figure 8 for NOL data source; values of $\overline{M}$ were assigned by fitting the data with a member of the one parameter family calculated with (6)-(8)

TABLE VIII

Average weight of fragments weighing more than one grain from steel cylinders* filled with various pressed explosives**

Explosive	Composition (parts by weight)	Density (g/cc)	Detonation Velocity (m/sec)	$\overline{M}$ (grains)
Amatol	80 Ammonium Nitrate/20 TNT	1.64		45
BTNEN/Wax	90 Bis trinitroethyl nitramine/10 Wax	1.66	8180	10.5
Composition A3	91 RDX/9 Wax	1.61	8270	12
Explosive D	Ammonium picrate	1.53		20
MOX-2B	54 Al/36 Ammonium Perchlorate/6 (97 RDX/3 Wax) 4 TNT/2 Calcium Stearate/1 Graphite	1.99	4820	30
Nitroguanidine		1.42		20
RDX/Wax (97/3)	97 RDX/3 Wax	1.61		11.5
RDX/Wax (95/5)	95 RDX/5 Wax	1.64	8450	11.5
RDX/Wax (88/12)	88 RDX/12 Wax	1.59		13
RDX/Wax (85/15)	85 RDX/15 Wax	1.55	8330	15
Tetryl	2,4,6 Trinitrophenylmethylnitramine	1.64	7460	17
Pentolite	50 PETN/50 TNT	1.60	7400	16
TNT	Trinitrotoluene	1.54	6750	22

*9" long, 2" I.D., 2.5" O.D., AISI 1045 seamless, cold rolled, stress relief annealed, Rockwell harness approximately 100-B.

**See Figure 8 for NOL data source; values of $\overline{M}$ were assigned by fitting the data with a member of the one parameter family calculated with (6)-(8)